Chapter 2

Principle

2.1 Introduction

FSC formation mechanism is a standard display method to achieve higher efficiency in current displays device. Therefore, the details of FSC LCD system will be presented briefly in this section. On the other hand, the response of the human visual system for luminance, color, temporal-spatial frequency, and eye movement depend on the characteristics of the light stimulus. Several features of human visual system have been developed to describe the visual match between the scene and the display. Therefore, the mechanism focus on two major issues in realistic human perceptual process. One is the properties of the human color vision that the perceived images match our perception of the scenes, and the second one is the movement of the eye ball. Hence, the mechanism of CBU can be described as following part. Finally, the prior methods for CBU and their corresponding theories will be illustrated in the last part.

2.2 Field-Sequential Color LCD

Color representation in a novel color FSC LCD is done with a combination of optically compensated bend (OCB) mode LC cells [15-16]. On the other hand, a color sequential LCD reproduces each color component in a time sequence using synchronously pulsed colored backlights and a LC cell without color filters. The whole TFT-LCD of LED backlights architecture is shown in Fig. 2-1.

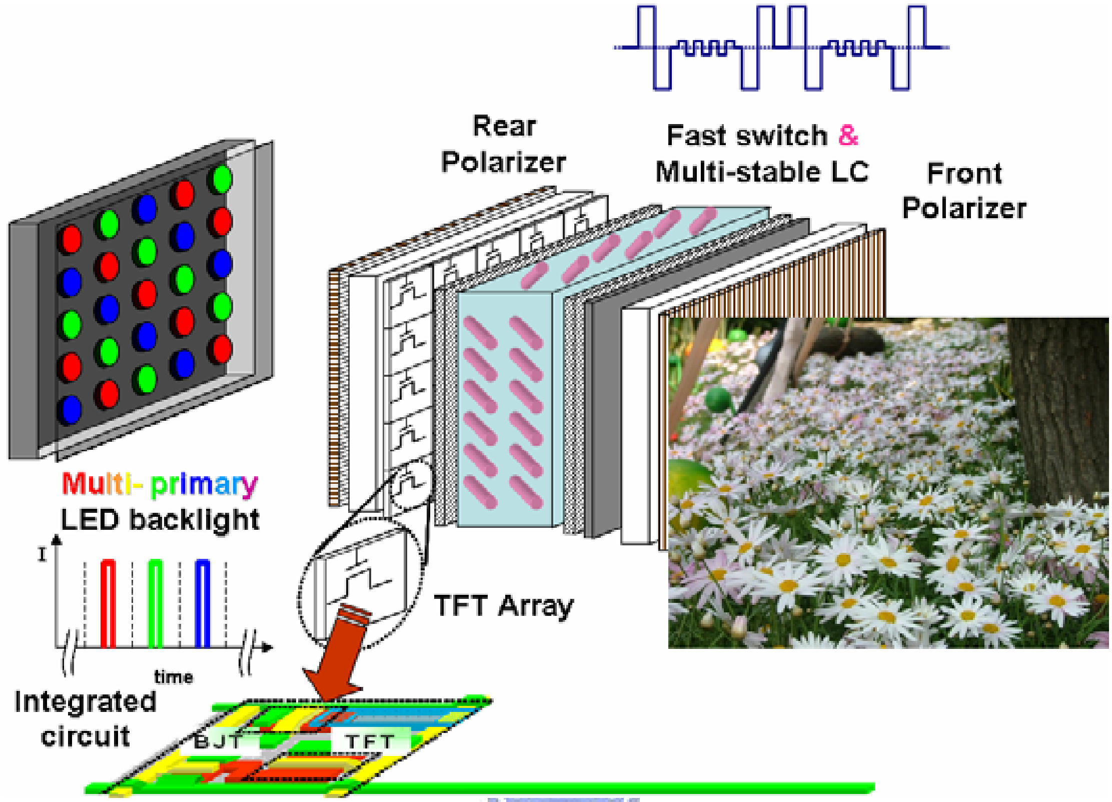

Fig 2-1. TFT-LCD with LED backlights Architecture.

Instead of having one third of the number of pixels, each pixel of the color sequential LCD should be driven three times as fast as a conventional LCD assuming the same frame rate. Unfortunately, the sequential color field scheme requires even shorter response time for the LCD panel and the backlight than in a conventional LCD because the sequential picture has larger variation among sub-frame for different colors even when the panel is displaying a still picture.

To drive active field sequential color LCD, driving schedule of scanning data, LC responses and backlight flashing time are important. Fig. 2-2. shows the timing chart. As shown in eq. (2-1), within one field time 1/3f, the scanning of whole panel, the responses of LC and the flash of the backlight must be completed.

$$\frac{1}{3f} = t_{TFT} + t_{LC} + t_{BL} \qquad (2\text{-}1)$$

Where, f is the frame frequency, t_{TFT} is the scanning time of whole panel, and t_{LC} is responses time of LC, and t_{BL} is the flash time of the backlight.

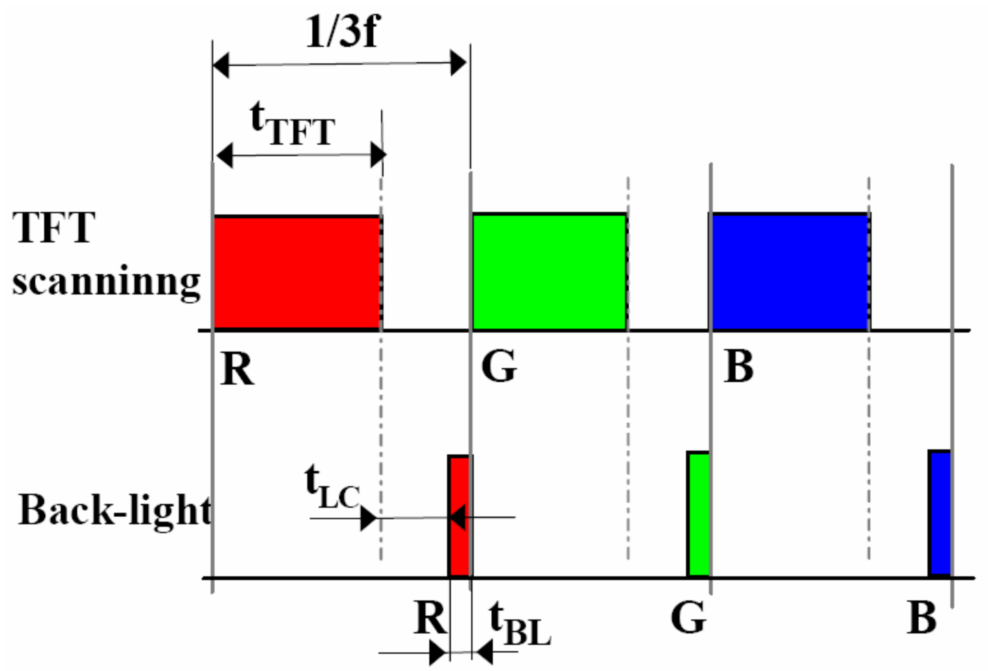

Fig. 2-2. Timing chart in the field sequential LCD with TFT addressing.

A fluorescent lamp is normally difficult to use for pulsed operation because the mercury vapor pressure drops during the blanking duration, and the light output decrease as a result. The fluorescence decay times of the red and green phosphors used in a conventional fluorescent tube are not fast enough for color sequential displays. Therefore, LEDs are used for these color sequential displays, because LEDs satisfy the fast responses time requirement for the color sequential operation. In addition, the emission spectra of LEDs are suitable for a display with high color purity.

In current novel FSC LCD, a color-filter-less LCD with R, G, and B LEDs as light sources has been developed as the FSC platform [17]. The LC of OCB mode was proposed for fast responses time to achieve a color field rate 180Hz. The diagonal size is 32” with resolution 1366*768 pixels and LEDs are implemented in 20*12 array layout. Finally, the maximum brightness is about 86.51cd/m^2 and the color gamut is almost 100% as compared to the NTSC standard.

2.3 Human Color Vision

Color vision is known best by human's perception of it [18]. It depends on wavelength more than on the energy of light but it is an illusion of reality resulting from a comparison of the responses of nerve cells in our brain. Color and all vision are in a sense illusory depending only on messages that pass between millions of neurons that reside within our skulls. These visual messages allow us to project ourselves into a universe that would be unknown to us without vision.

Much is known about human color vision both subjectively and quantitatively from the fields of physics, psychology, and physiology. Physiology attempts to explain color vision by the responses of neurons. This is the ultimate step in understanding color and eventually perhaps in constructing machines that will see a similar universe of colors.

2.3.1 Structure of Human Eye

Before the introduction of the mechanism of eye movement, the role of eye on human perceptual process must be discussed and learned first. As we known, the optical image formed by the eye is projected onto the retina. The retina is a thin layer of cells located at the back of the eye and incorporating the visual system's photosensitive cells and initial signal processing and transmission circuitry. These cells are neurons, part of the central nervous system, and can appropriately be considered a part of the brain. The photoreceptors, rods and cones, serve to transduce the information present in the optical image into chemical and electrical signals that can be transmitted to the later stages of the visual system. Fig. 2-3 illustrates a cross-sectional representation of the retina.

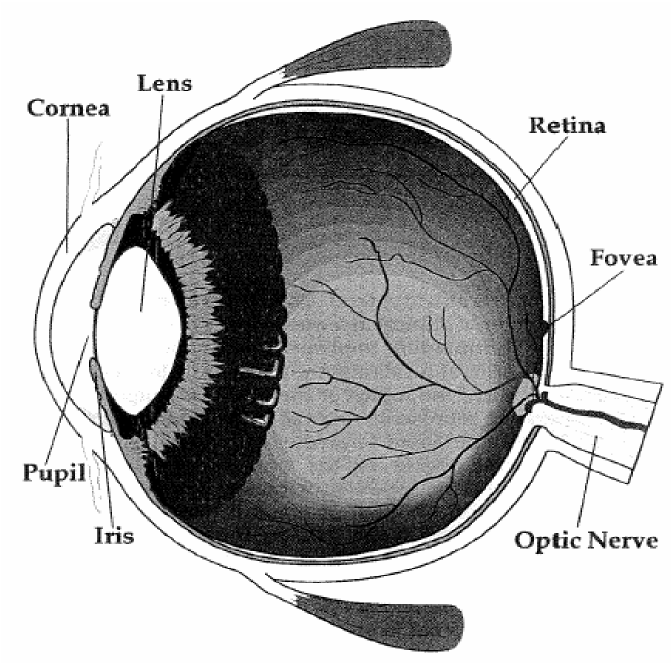

Fig. 2-3. Schematic diagram of the human eye with key structures.

The retina includes several layers of neural cells, beginning with the photoreceptors, the rods and cones. The important distinction between rods and cones is in visual function. Rods serve vision at low levels(less than 1 cd/m^2) while cones serve vision at higher luminance levels. Thus the transition form rod and cone vision is one mechanism that allows our visual system to function over a large range of luminance levels. At high luminance levels(greater than 100cd/m^2), the rods are effectively saturated and only the cones function. In the intermediate luminance levels, both rods and cones function and contribute to vision. Vision when only rods are active is referred to as scotopic vision. Vision served only by cones as referred to as scotopic vision and the term mesopic vision is used to refer to vision in which both rods and cones are active.

Rods and cones also differ substantially in their spectral sensitivities as illustrated in Fig. 2-4. There is only one type of rod receptor with a peak spectral responsivity at approximately 510 nm. Yet, there are three type cones as L, M, and S cones. These names refer to the long-wavelength, middle-wavelength, and short-wavelength sensitive cones, respectively. Since there is only one type of rod, the rod system is incapable of color vision. In contrast, the three types of cones can clearly serve color vision to observe a normally colorful scene.

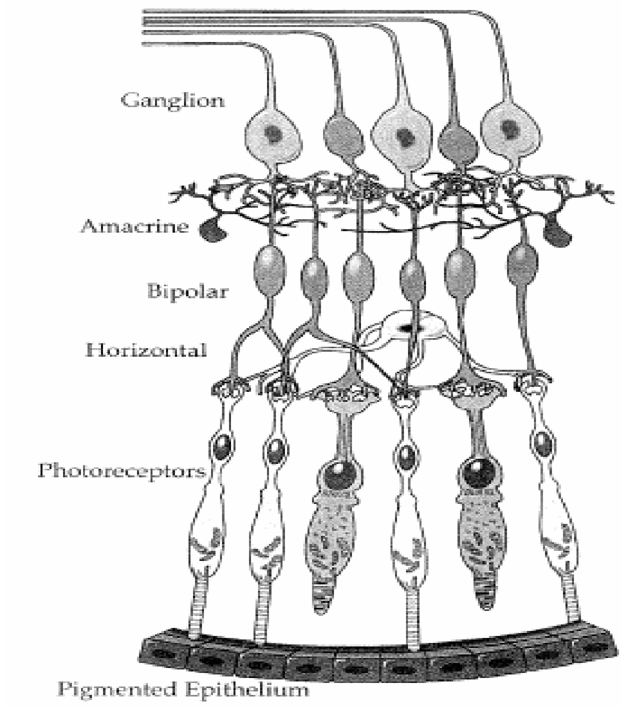

Fig. 2-4. Schematic diagram of the wiring of the cells in the human retina.

Another important feature about the three cones types is their relative distribution in the retina. It turns out that the S cones are relatively sparsely populated throughout the retina and completely absent in the most central area of the fovea. There are far more L and M cones than S cones. The relative populations of the L:M:S cones are approximately 12:6:1. These relative populations must be considered when combining the cone responses.

The density of rods and cones distribution on the retina can be observed in Fig. 2-5. Measured density curves for the rods and cones on the retina show an enormous density of cones in the fovea center. Notice the extremely large numbers of photoreceptors. It is attributed both color vision and the highest visual acuity. Visual examination of small detail involves focusing light from that detail onto the fovea central. On the other hand, the rods are absent from the fovea. At a few degrees away from it, their density rises to a high value and spreads over a large area of the retina. These rods are responsible for night vision, our most sensitive motion detection, and our peripheral vision.

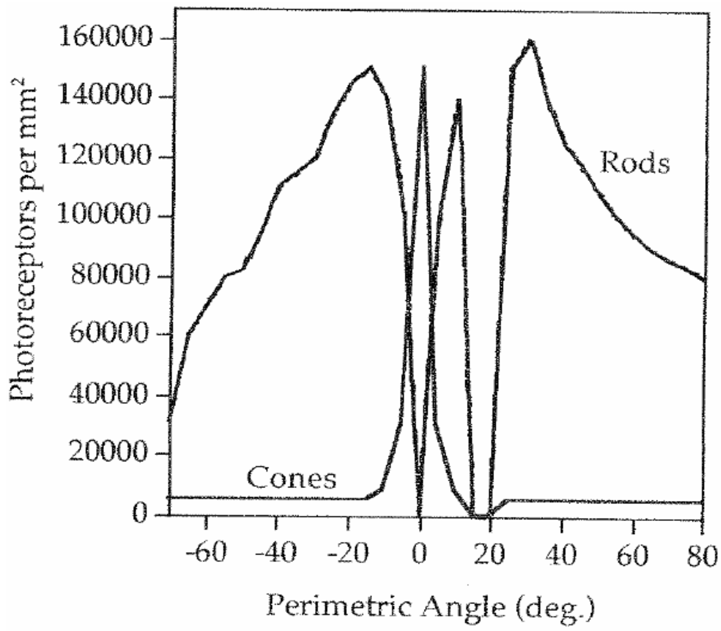

Fig. 2-5. Density of rod and cone photoreceptors as a function of location on the human retina [18].

2.3.2 Visual Signal Processing

The optical image on the retina is first transuded into chemical and electrical signals in the photoreceptors. The ganglion cell axons gather to form the optical nerve, which projects to the lateral geniculate nucleus (LGN) in the thalamus. The LGN cells, after gathering input from the ganglion cells, project to visual area one (V1) in the occipital lobe of the cortex. At this point, the information processing begins to become amazingly complex.

Light incident on the retina is absorbed by photo pigments in the various photoreceptors. In rods, the photo pigment is rhodopsin. Upon absorbing a photo, rhodopsin changes in structure, setting off a chemical chain reaction that ultimately results in the closing of ion channels in its cell walls which produce an electrical signal based in the relative concentrations of various ions inside and outside the cell wall. A similar process takes place in cones. Rhodopsin is made up of opsin and retinal. Cones have similar photo pigment structure. However, in cones the conopsins have slightly different molecular structure resulting in the various spectral responsivities observed in the cones. Each type of cone contains a different form of cone-opsin. Fig. 2-6 illustrates the relative responses of photoreceptors as a function of retinal exposure.

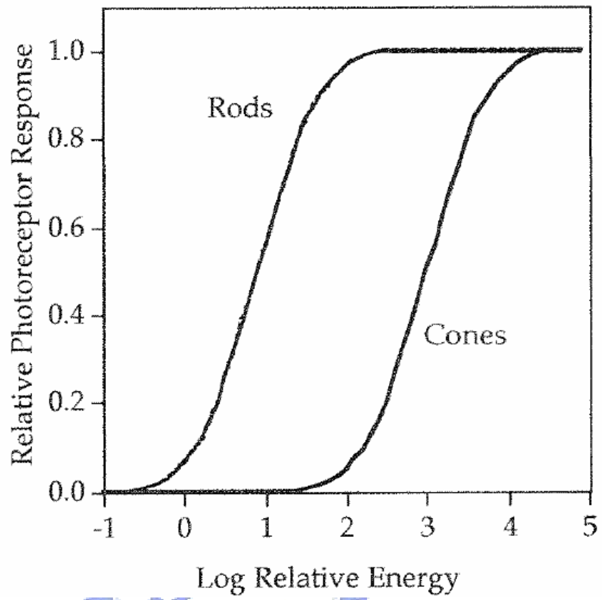

Fig. 2-6. Relative energy responses for the rod and cone photoreceptor.

2.3.3 Opponent-Colors Theory

Fig. 2-5 illustrates the first stage of color vision, the receptors, is indeed L, M, and S cones. However, the three color separation images are not transmitted directly to the brain. Instead the neurons of the retina encode the color into opponent signals. The outputs of all three cone types are summed (L+M+S) to produce to the relative population of the three cone types. Differencing of the cone signals allows construction of red-green (L-M+S) and yellow-blue (L+M-S) opponent signals. The transformation from LMS signals to the opponent signals serves to decorrelate the color information carried in the three channels, thus allowing more efficient signal transmission. The three opponent pathways also have distinct spatial and temporal characteristics that are import for predicting color appearance.

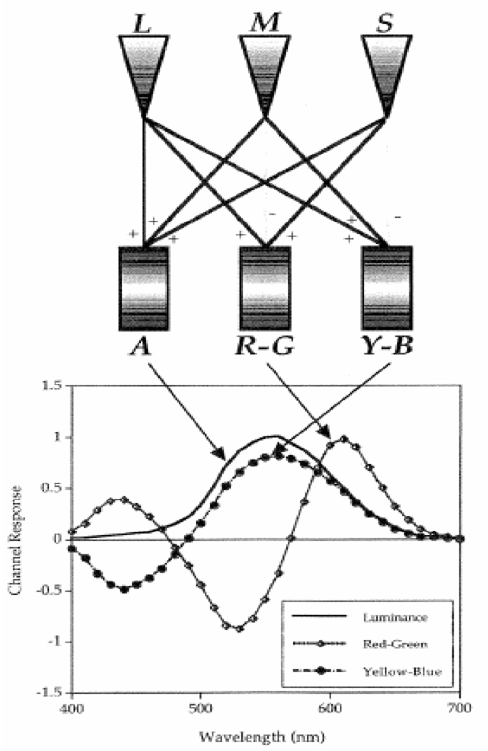

Fig. 2-7. Schematic illustration of the encoding of some signals into opponent-colors signals in the human visual system.

2.3.4 Spatial and Temporal Properties of Color Vision

The color appearance of a stimulus is not independent of its spatial and temporal chrematistics. In general, the spatial and temporal chrematistics of the human visual system are typically explored through measurement of Contrast Sensitivity Functions (CSF). A contrast sensitivity function is defined by the threshold response to contrast as a function of spatial or temporal frequency. Contrast is typically defined as the difference between maximum and minimum luminance in a stimulus divided by the sum of the maximum and minimum luminance.

Fig. 2-8 illustrates typical spatial contrast and sensitivity functions for luminance (black-white) and chromatic at constant (red-green and yellow-blue). The luminance contrast sensitivity function is band-pass in natural, with peak sensitivity around 5 cycles per degree. However, the band-pass contrast sensitivity correlates with the concept of center-surround antagonistic receptive fields that would be most sensitive to an intermediate range of spatial frequency. In contrast, the chromatic mechanisms are of a low-pass nature and have significantly lower cutoff frequencies. This indicates the reduced availability of chromatic information for fine details that are often taken advantage of an image coding and compression schemes.

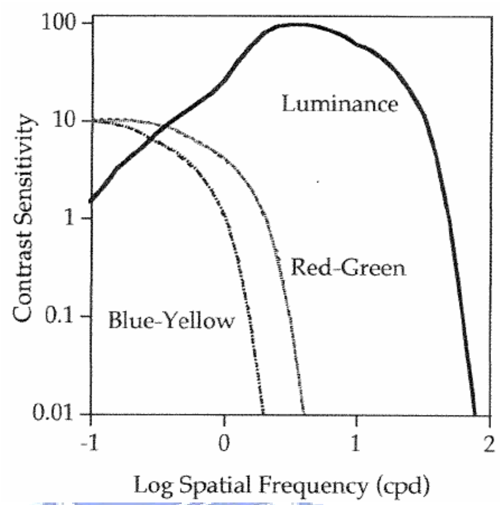

Fig. 2-8. Spatial contrast sensitivity functions for luminance and chromatic contrast.

The low-pass characteristics of the chromatic mechanisms also illustrate that edge detection/enhancement does not occurs along these dimensions. The blue-yellow chromatic CSF has a cutoff frequency than the red-green one due to the scarcity of S cones in the retina. It is also of note that the luminance CSF is significantly higher than the chromatic CSFs, indicating that the visual system is more sensitive to small changes in luminance contrast compared with chromatic contrast.

Contrast to the spatial properties, Fig. 2-9 conceptually illustrates typical temporal contrast sensitivity functions for luminance and chromatic contrast. Again, the luminance temporal CSFs, and it shows the band-pass characteristics suggesting the enhancement of temporal transients in human visual system. As stated earlier, the dimensions of human visual perception cannot be examined independently. The spatial and temporal CSFs interact with one another. A spatial CSF measured at different temporal frequencies well varies tremendously and the same is true for a temporal CSF measured at various spatial frequencies. These functions also depend on other variables such as luminance level, stimulus size, and retinal locus.

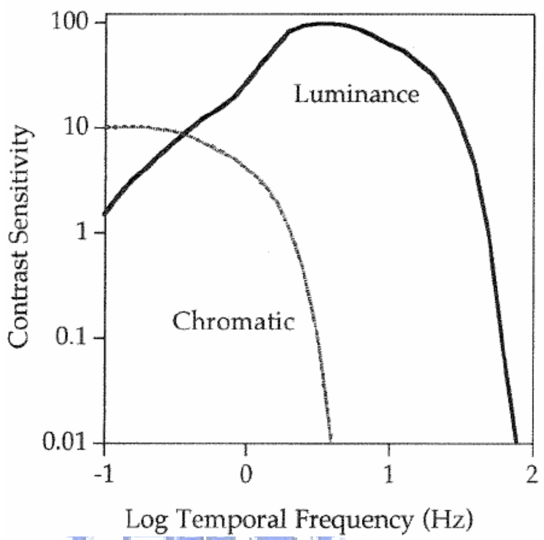

Fig. 2-9. Temporal contrast sensitivity functions for luminance and chromatic contrast.

The spatial and temporal CSFs are closely linked to the study of eye movements. A static spatial pattern becomes a temporally varying pattern when observers move their eyes across the stimulus. Noting that both the spatial and temporal luminance CSFs approach zeros as either form of frequency variation approaches zero. It follows that a completely static stimulus is invisible. This is indeed the case. If the retinal image can be fixed using a video feedback system attached to an eye tracker, the stimulus does not appear after a few second. To avoid this rather unpleasant phenomenon in typical viewing, our eyes are constantly moving. The detail mechanisms of eye movements will describe clearly below.

2.4 Eye Movement

Since the area of the fovea is about two degrees of visual angle in the central view of vision. When we look at an image in our visual field, our eyes move volitional or spontaneous such that the image of the object falls on the fovea.

In general, eye movement can be classification into several types, like Vestibular-Ocular Reflex (VOR), Opto-Kinetic Nystagmus (OKN), visual fixation, smooth pursuit, saccade, and so on. However, the movements of the eye leading to perceived CBU are only two types. One is saccade movement, and the other is smooth pursuit movement [19].

2.4.1 Saccade

Saccade eye movements are rapid and random conjugate eye movement used in scanning and localizing target or in the absence of the target involuntarily. In human eyes, it does not look at a scene in a steady way. Instead, the eyes move around, locating interesting parts of the scene with greater resolution to form a meaning image corresponding to the scene onto the retina. The illustration of saccade movement is shown in Fig. 2-10. All lines were shown the path of saccade movement for stimulus. A line to tie a white dot to form a dot is eye movements as to perceive the image. Points where the eye fixed for some periods are shown as dot. After the cycles, a full image can be perceived clearly. Generally, the larger saccade, the higher the velocity of the eye movement, with saccades of 700° /sec occurring in 80 degree movement [19].

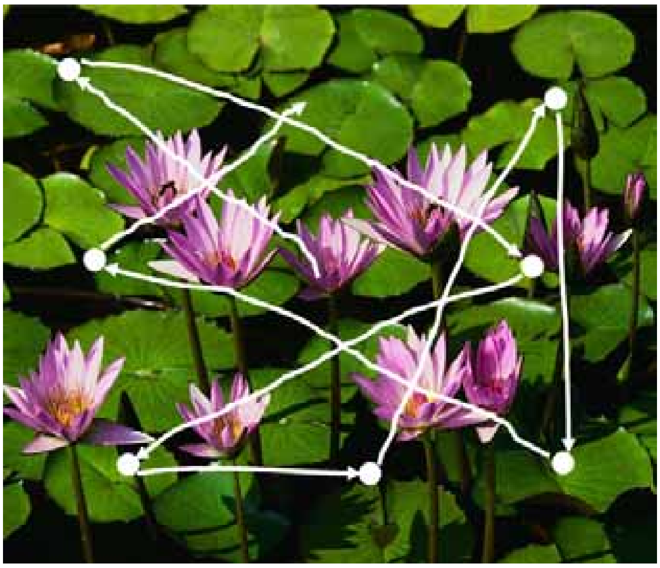

Fig. 2-10. An example of saccade eye movement.

2.4.2 Smooth Pursuit Movement

Pursuit movement is the ability of the eyes to follow a moving object around. It is a slow, generally about 30° to 40° /sec, with a reaction time to a moving stimulus of approximately 125 msec eye movement, through smooth pursuit has been recorded at velocities of 100° /sec [20]. The eye move conjugately if the target is moving at a constant distance form the subject, and at a speed that matches the velocity of the moving target.

Unlike saccades, smooth pursuit usually can not be generated in the absence of a stimulus and has not been found species without foveas. Smooth pursuit serves to maintain foveal fixation of a slowly moving target, but this fixation comes at the cost of blurring the background.

2.5 Mechanism of Color Break-Up

As mentioned early, FSC displays, there are, at least, 3 color fields constituted a full color frame. While the field rate is high enough, and the 3 fields projected onto the retina in the same position, HVS will produce a complete full color image. On the other hand, if there exists relative motion between the observer and the monitor, causing the 3 color fields shifted in position on the retina, the observer is probably to have the sensation of this field separation; then, results in color breakup.

CBU occurs in relation motion between the movement of object within the imagery and the observer's eye movement both with stationary and moving images on FS color displays. The detail mechanisms of CBU are described below.

2.5.1 Stationary image

For stationary image, the eye ball will perform saccade movement in an angle of vision and we will have a chance to perceive CBU along motion direction. For example, gray line indicates the pass of a saccade in Fig. 2-11 (a). If the eye ball moving path through left to right, the original image seems to break-up into three color fields alone the motion direction at the instants of saccade eye movement, such as Fig. 2-11 (b).

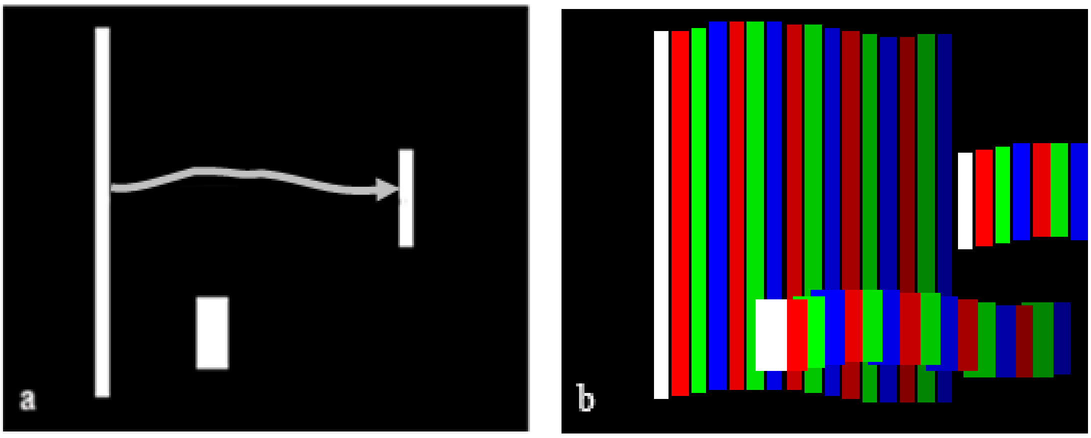

Fig. 2-11. (a) Image in a field-sequential display and path of a saccade, and (b) Observed color break-up during or just after the saccade [8].

2.5.2 Moving image

Contrast to the stationary image, CBU is perceived whatever the eyes are always tracking a moving image such as Fig. 2-12 (a). Two frames for instance, different color fields can be perceived separately on the edge by pursuing eye movement and temporal integration in the visual system. The two dimensions showed in Fig. 2-12 (b) illustrate the mechanism of the CBU generation during eye tracking movement.

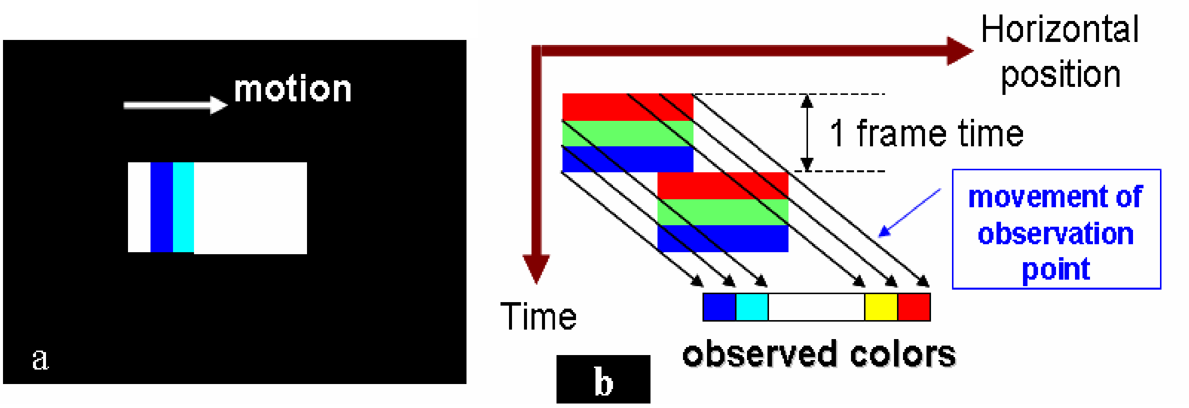

Fig. 2-12. (a) Moving image and motion direction, and (b) Mechanism of CBU [12].

2.6 CBU Qualitatively and Quantitatively Analysis Methods

2.6.1 Subjective Evaluation

A psychophysical visual experiment is a direct method to quantify CBU at the outset. To investigate CBU on FSC display, X. Zhang and J. E. Farrell conducted a psychophysical experiment by using subjective evaluation to quantify visibility of these color artifacts for different saccadic speed, display background brightness, and target size [6]. A sequential color projector was placed behind a projection screen to simulate a normal desktop display. Saccade eye movement was induced by requiring subject to recognize text targets displayed at two different screen locations in repaid succession. The speed of saccadic movements was varied by manipulating the distance between the two target locations.

A white bar, either with or without a yellow and red color fringe on the right edge, was displayed as subjects moved their eyes for the text recognition task. The two versions of the white bar will not be distinguishable if CBU is present, thus performance of this task can be used as measure of CBU. The visibility of sequential CBU decreases with background intensity and size of the white target, and increases with saccadic speed.

2.6.2 Analysis Dynamic CBU by ΔE

In studying CBU, there are two things to consider about to quantify amount of CBU. One is brightness of the broken color and the other one is width of CBU [7]. In L*u*v* space, the amount of CBU could be quantified by color difference metric which is known as delta E (ΔE). The color different between source color and destination color should be accumulated along the off-route color broken line. The number of the points on the off-route line indicates the amount of CBU width. The algorithm introduced in here considers the amount of chromaticity deviation, lightness and color broken width. Therefore, the level of CBU can be analyzed more precisely.

2.6.3 Precise Recording

A unique device for measuring CBU on stationary system has been presented in 2004 [8]. In this CBU measurement system, a monochrome camera capable of taking more than 10,000 images per second is used for the whole range of available target displays. The view of the camera is moved with a two-axis tilting mirror to simulate an eye saccade, thus a saccade can be made between any two points in the target display. Besides, the camera is synchronized with the target display and an image is captured from every sub-frame by a photodiode. Therefore, captured images can be used in study of CBU mechanism.

2.7 CBU Suppression Methods

2.7.1 Field Rate Increasing

CBU can be perceived in relative motion between the target image and the observer. Yet, R, G, and B fields displaying sequentially not fast enough is the main cause in FSC display for CBU. Thus, CBU in FSC displays is expected to be reduced by decreasing the displaying light [11]. Some researchers have performed experiments in which observers adjusted an FSC display's field rate until CBU was either just above or just below threshold. The display was a specially designed Maxwellian-view optical system that generated a moving FSC stimulus at field rates up to 6 KHz.

CBU were measured as a function of the stimulus's luminance, contrast, and retinal velocity. A regression equation that describes the observer's mean threshold field rates was being developed, so that the equation constitute design tools that can be used to assess the adequacy of prospective FSC display field rates for specific application.

2.7.2 ACE Method

A new method which is called Adjust of Color Element on the Eyes (ACE) has been developed to reduce the negative effects of CBU associated with moving objects for FSC

LCDs by N. Koma and T. Huchida [13]. By using this method, the RGB images are displayed at different serene points. As the eye tracks the moving object, the RGB sub-images are focused in the same point on the retina therefore CBU does not appear.

2.7.3 Multi-Primary Color Fields

Field sequential projection displays exhibit a phenomenon of CBU. This is considered to be a distributing artifact with negative marketing impact. Therefore, D. Eliav, E. H. A. Langendijk, S. Swinkels, and L. Baruchi, they perform a psychophysical experiment to compare the visibility of the CBU in a three-primary (RGB) projection display, which operating with a higher frame frequency, and two five-primary (RGBYC) displays operating at lower frame frequency [14].

D. Eliav, E. H. A. Lanqendijk, S. Swinkels, and I. Baruchi assumed that the eye brightest field (green in the RGB display and yellow in the five-primary display). Each of the primary fields is split into three channels, i.e. a luminance channel, red-green channel and a yellow-blue opponent channel. Each one is filtered spatially with the corresponding response. For five-primary displays, they use the measured XYZ values to estimate the luminance and opponent signals, while for the RGB display; they use the same chromaticity of the five-primary RGB components, and adjust the relative luminance levels to obtain equal white points at equal brightness. Subsequently, they integrate the luminance and opponent signals of all fields to mimic a low-pass temporal response. The results show a strong modulation in the red-green channel, with a weak blue-yellow modulation on the edges of the white strip in the RGB display, while in the five-primary display mostly a yellow-blue modulation is seen. That is consistent with the observation that red and green shadows are seen in the RGB displays, while for the five primary displays the shadows are in blue and yellow. The modulation pattern is determined by the order of the primary colors and the tracking of the brightest field. An optimization of color order may therefore further reduce the CBU. According to the experiment result, the five-primary displays produce less CBU than that, even three-primary displays at lower frame rates.

2.8 Summary

The mechanism of human color vision and principle of CBU were presented. Due to the color breakup artifact exists in FSC displays, several prior arts, classification and improvement has mentioned of the mechanism in the past decade. However, all of them just only focus on the quantification or improvement of CBU. Hence, we would like to build a visual model to link all the steps. First, predict the amount of CBU from a single frame image in physical conditions. Next, psychophysical experiments were performed to define reasonable criteria for distinguishing perceptibility of CBU under various parameters. Finally, CBU suppression scheme was applied in sample target pattern to improve the image quality. The detail of each step will be presented in following chapters.