Color Breakup: Taxonomy, Measurement, and Remedy

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Abstract

Despite its 3X optical efficiency, 3X pixel resolution, and 20% cost reduction, the field-sequential liquid crystal display (LCD) suffers from the color breakup phenomenon (CBU), which occurs when the red, green, and blue components of the same object project onto different retinal areas upon eye movement. To measure the human vision sensitivity to CBU, we conducted psychophysical experiments based on a linear dual-color saccadic display. To suppress CBU, we designed an electrooculogram (EOG) circuit to detect the saccadic eye movement. When saccades are detected, the contingent display reduces the image chroma on-the-fly by modulating the red/green/blue LED backlights such that the CBU artifacts are unperceivable. Otherwise, the contingent display stays in the normal mode to offer the best image quality. It is a pioneering work using brain-machine interface to solve the long pending challenge to the field-sequential LCD.

Introduction

The field sequential display synthesizes colors in the time domain. By quickly flashing the red, green, and blue fields, one after another, the observer is unable to distinguish the time difference between the three channels. This technology has been successfully used in TI's DLP-based projectors, which use fast-switching micro mirrors to produce graylevels and a color wheel to produce the primaries. In this way, resources can be shared by the three channels and the hardware cost can be greatly reduced. If such technology can be adapted for the liquid crystal display (LCD), not only its luminance efficiency can be increased to 3X, which equates to considerable power savings, but also the hardware cost can be cut down to 80% because the costly color filter process on the glass substrate can be eliminated.

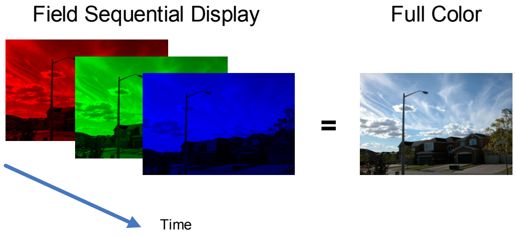


***Figure 1**. Field sequential displays synthesize colors in the time domain.*

Unfortunately, unlike DLP, the slow response time of liquid crystals limits the highest frame rate of field sequential LCD. The most infamous artifact on field sequential displays, the *color breakup* phenomenon (CBU), occurs when the red, green, and blue components of the same object project onto different locations of retina upon eye movement. Due to different types of eye movements, color breakup may present in different forms. Figure 2 and 3 depict the simulated color breakup phenomena in smooth pursued and saccadic eye movement, respectively.

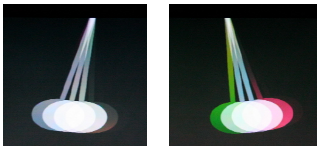


***Figure 2**. Simulated pursued color breakup.*

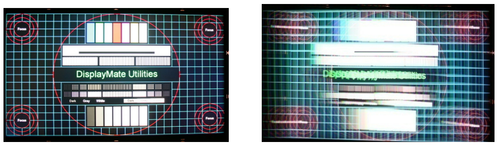


***Figure 3**. Simulated saccadic color breakup.*

Originated in the 80s, the study of field sequential display revived in the recent years for the temptation of high optical efficiency, high spatial resolution, and low manufacturing cost to the field sequential LCD [1]. Despite its long research history, the foundation of CBU is still difficult to analyze due to the tangling causing factors such as the target movement, eye movement, field rate, target luminance, target pattern, primary colors/waveforms, ambient light, eccentric angle, viewing conditions, etc.

In literature, the CBU-related studies can be categorized as follows.

(a) <u>Analytical method</u>: The moving target is mathematically modeled by its colorimetric parameters and moving velocity [2]. Assuming perfectly pursuing eye movement, the perceived CBU is predicted by Grassman's law of additive colors, which unfortunately does not hold under eye movement.

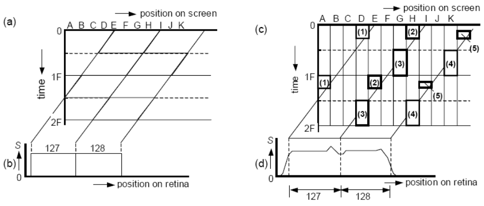


***Figure 4**. Predicting color breakup by colorimetrical calculation [2].*

(b) Photonic measurement: High-speed cameras are used to emulate the eye movement and to capture the process of colors falling apart [3]. Such experiments built the basis of photometry-based analysis, which however is still discrepant from the visually perceived artifacts.

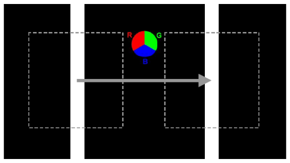


Figure 5. *Measuring color breakup with high-speed camera [3].*

(c) Subjective measurement: Commonly used in subjective experiments is a white box moving linearly on black background to provoke the worst CBU. The task of human subjects is to judge if any chromatic stripes perceived on the edges [4]. In our experience, such setup failed to reproduce reliable data because (i) perfectly pursuing the linear target movement on small displays is difficult, which results in variation of CBU judgment, and (ii) focusing on whether the edge is colored or not hinders us from considering the other important parameters such as stimulus size and spatial frequency.

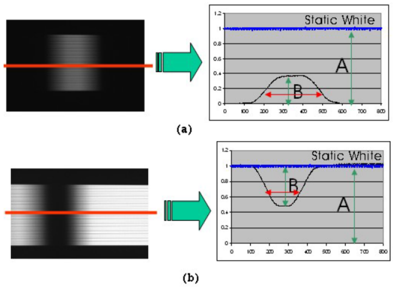


Figure 6. *Measuring color breakup by subjective rating [4].*

(d) Psychophysical measurement: The foundation of color science is based on psychophysics, because even when judging colors of still stimuli, the bias of human subjects can lead to significant variation. Thus, to accurately access the spontaneous CBU phenomenon, carefully designed psychophysical experiments are required [5-8].

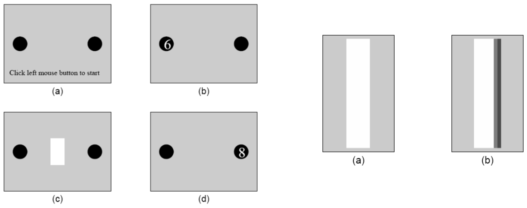


Figure 7. *Measuring color breakup by psychophysical methods [5].*

The focus of this paper is on pursued CBU and saccadic CBU, which will be described in Section 2 after a taxonomic summary on color-related artifacts. Section 3 proposes two novel experimental techniques for measuring CBU and Section 4 describes our interactive solution to saccadic CBU.

Taxonomy of Color Artifacts

Considering the display a visual communication system, our discussion separates stimulus from perception of human vision system (HVS). On the stimulus side, the first-order parameters include luminance, chromaticity, temporal frequency (field rate), spatial frequency (grating), and moving velocity. On the perception side, since HVS is three-dimensional, the detection thresholds are different between the luminance and chromaticity domain. Table 1 enumerates the common artifacts detected in different conditions.

Table 1: Categorization of Display Artifacts

	Detected in Luminance	Detected in Chromaticity
Spatial color; Still target	Mura	Color shift
Sequential color; Still target	Luminance flicker	Chromatic flicker
Spatial color; Still target	Aliasing	Subpixel dithering
Sequential color; Moving target	Motion blur	Color breakup

The first row represents scenarios like inspecting a white screen on a conventional color spatial LCD. The *mura* is detected if any luminance difference is perceived at different locations. Color shift (e.g. due to viewing angle difference) may still be perceived even when mura is absent from perpendicular measurement because HVS has higher sensitivity to chromatic difference at low spatial frequency. The contrast sensitivity functions (CSF) of still target in the luminance and chromaticity domain had been well studied. In both temporal and spatial domains, luminance CSF is a band-pass filter while chromaticity CSF is low-pass.

The second row speaks for still patterns on a field sequential display. If the field rate is lower than the *critical flicker fusion frequency* threshold, luminance flicker may be perceived. Note that the RGB primaries have different luminance so luminance flicker is always detected before chromatic flicker. In other words, isolating chromatic threshold from luminance on a field sequential display is challenging.

The third row brings up the spatial resolution issues on conventional LCDs. The aliasing artifact is only perceivable when the human eye can resolve the pattern on pixel level. Recall that luminance CSF is more sensitive than the chromaticity CSF at medium spatial frequencies. The principle of subpixel dithering is to supplement luminance information without chromaticity being detected.

The (relative) movement of the target comes into play in the last row. In this case, the gaze position of the observer determines how the artifacts are perceived. The stimulus is called *stable* if the target and gaze position are in sync, i.e., the target is perfectly pursued by the eye movement. Otherwise, the stimulus is called *unstable*. Unstable stimulus can be caused by different types of eye movements – fixation, smooth pursuit, and saccade. Notice that the HVS has very different sensitivity in these three movements. The retinal velocity in smooth pursuing eye movement was taken into account in studies of *motion blur*, where achromatic stimuli were considered at different spatial and temporal frequencies [9].

CBU, a variation of motion blur on a field sequential display, is included by the fourth row. Since in HVS both temporal and spatial sensitivities are higher in luminance domain than in chromaticity, in visual experiments human subjects always perceive luminance flicker on the edges before transitioning from CBU-free stimuli to CBU-embedded ones. This is another reason why subjective experiments produce divergent results, because it is difficult for the subjects to report whether the perceived artifacts are chromatic or not.

In this paper we focus on the smooth pursued CBU and saccadic CBU. The former has received major attention for decades while the latter has not been well treated not only because of its instantaneous and swift nature but also its still unknown underlying neural mechanism.

Measurement of Color Breakup

Two psychophysical experiments were designed to measure the thresholds of pursued CBU and saccadic CBU.

Measuring Pursued Color Breakup

An experimental platform was designed to present stimuli with either sequential primaries or simultaneous primaries. A 19" TN-type LCD monitor (ViewSonic VX912) was reworked for our purpose. Two lightbars, each with 24 LED chips, take place of the original CCFL backlights on the top and bottom edges of the panel. Three-in-one RGB LED chips (5WRGGB, Arima Optoelectronics Corp.) were used. To detour heat dissipation from the light-bar, the heat sink compound was applied to the gap between the thermal pads of LEDs and the lightbar, which attach to the metal frame tightly for better heat dissipation.

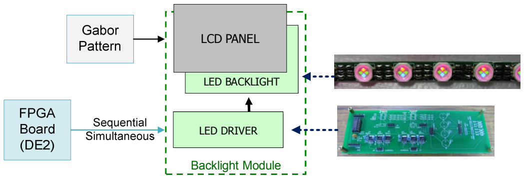


Figure 8. *Platform for measuring pursued color breakup.*

The stimulus is an achromatic vertical Gabor pattern moving along a circle as shown in Figure 9.

Figure 9. *Achromatic Gabor pattern in circular motion.*

Adjustable parameters include color, contrast, speed (angular velocity and radius), size, and spatial frequency. In the *sequential* mode, which emulates a field sequential display, the red, green, and blue LED backlights are triggered one after another with adjustable frequency, duty cycle, intensity, and order. In this mode, perceiving color breakup is possible (Figure 10 left). In contrast, in the *simultaneous* mode, which emulates a conventional display, the backlights are triggered at the same time, so color breakup is impossible to be observed (Figure 10 right). In both modes, the triggering frequencies are the same, so they both have the same degree of flicker. The subjects will not be able to use flicker as a cue to guess, so we can separate the artifacts in the chromaticity domain (color breakup) from the luminance domain (flicker).

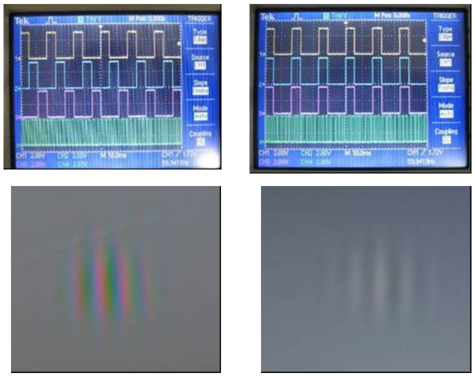


Figure 10. *Sequential (left) vs. simultaneous color (right). The RGB driving patterns generate different stimuli on the same moving gray Gabor pattern.*

Measuring Saccadic Color Breakup

To cope with the high-speed saccadic eye movement, we designed a saccadic display [10], which is a linear array of 32 red/green LEDs controlled by an FPGA board (DE2, Terasic/Altera). A 32x32 dual-color image is stored as a bitmap in the FPGA (Figure 11).

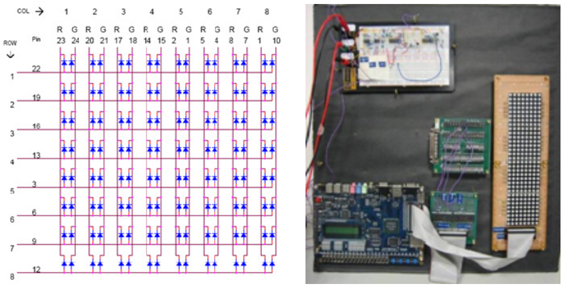


Figure 11. *Layout and prototype of a red/green LED-based saccadic display.*

When triggered, the LED array displays the 32 vertical columns, one by one, from right to left, every 100ns (or other tunable period). If a right-bound saccade across the display initiates with perfect timing, then the original two-dimensional image will be reconstructed on retina (Figure 12).

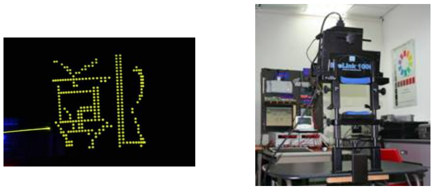


Figure 12. *Left: Sample image of saccadic display captured by a camera with extended exposure. Right: A video-based eye tracker used to record and capture eye movements.*

We used this apparatus to measure the saccadic CBU threshold. Two reference marks are placed on both sides of the saccadic display to determine the saccade amplitude and thus the saccade speed. An audible beep generated by the FPGA was used to cue the subject to initiate a saccade from the left mark to the right one. Resemble alphabets (e.g. 1 vs. 7 or 3 vs. 8) in 32x32 bitmaps are used as stimuli. A series of 32 linear patterns are fired sequentially on the saccadic display after the audible beep. Subsequently the subject is asked to pick the answer from two candidates according to the forced choice method. The threshold is found by tuning the LED luminance in repeated trails. As a key parameter, the luminance/chromaticity of ambient light is controlled during the experiments. A video-based eyetracker (Eyelink 1000, SR Research) is used to record the actual eye movements. The subject response and triggering events are also fed into an A/D converter for annotating the eye movement events.

Remedy for Saccadic Color Breakup

We designed a contingent field sequential display that inhibits color breakup by reducing chroma on-the-fly when saccadic eye movement is detected by using *electro-oculogram* (EOG). EOG is a technique for measuring the resting potential of the retina. A pair of electrodes is placed to the left and right of the eyes, and an indifferent electrode is placed on the wrist as reference. By measuring change of the potential difference caused by rotation of the eyeballs, the eye movement events can be detected (Figure 13).

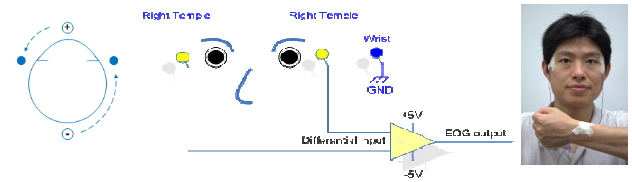


***Figure 13**. Resting potential of the retina and the EOG configuration.*

When the eye moves to the right, the right electrode picks up a positive signal while the left electrode picks up a negative signal. As a result, the potential difference between two electrodes indicates changes of the eye position (Figure 14).

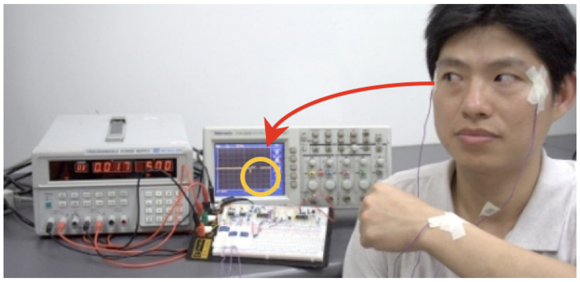


***Figure 14**. The EOG circuit picks up the potential changes caused by saccadic eye movements.*

The electrical potential level of EOG is very low (50~3500uV) so it has to be carefully amplified and filtered to reject the ambient noises including the electromagnetic radiation noise from the 60Hz power line, the electrical signals generated by muscle activities and other organs [10]. Our EOG circuit includes instrument amplifiers (AD620, Analog Devices), a 10Hz low-pass filter, a 2Hz high-pass filter, a twin-T band-rejection (notch) filter, and gain amplifiers (OPA 4137, TI). The circuit block diagram is shown in Figure 15.

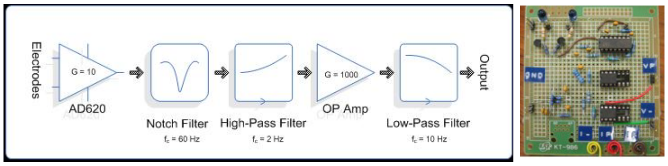


***Figure 15**. Block diagram and prototype of the EOG circuit.*

An electroencephalography (EEG) recorder (EGI 200 64-channel, EGI) was used to calibrate and verify our EOG circuit. EEG is the technique of measuring the electrical signals produced by the brain activities. The electrical potentials are measured from the scalp with 64 electrodes on a head-net. Among these channels, we considered only the two channels near canthi (the ends of eyebrows) because they receive the EOG signals that we need.

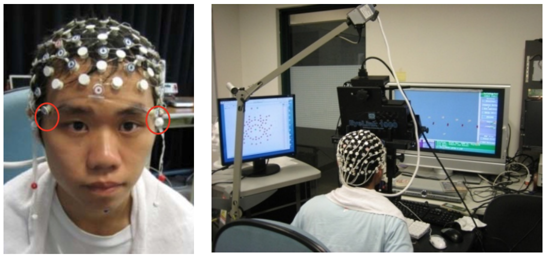
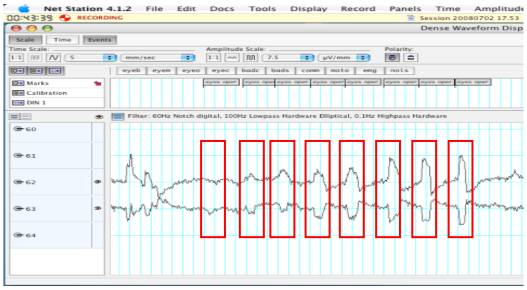


***Figure 16**. Two channels of electroencephalography were used to calibrate the EOG circuit.*

The subject performed 8 predefined saccades in different amplitudes. The EEG output signals from these two channels were measured as shown in Figure 17.



Session 20080702 17.53

Time Scale: 1:1 5 mm/sec

Amplitude Scale: 1:1 7.5 µV/mm

Polarity:

Filter: 60Hz Notch digital, 100Hz Lowpass Hardware Elliptical, 0.1Hz Highpass Hardware

***Figure 17**. The two channels for eye movements show similar but opposite waveforms.*

To characterize our EOG circuit, we asked the subjects to perform predefined saccades and measured the EOG output. The results are listed in Table 2. Between 7.5° and 30°, the EOG output and saccade amplitude are linearly correlated.

Table 2: Measured EOG output for predefined saccades

Saccade amplitude (deg)	Left-bound EOG output (mV)	Saccade amplitude (deg)	Right-bound EOG output (mV)
-7.5°	440	7.5°	560
-15.0°	760	15.0°	960
-22.5°	1040	22.5°	1240
-30.0°	1440	30.0°	1920

To evaluate the accuracy of our EOG circuit, we used a video-based eyetracker (Figure 12) as the baseline. Both eyetracker and EOG signals were recorded by an oscilloscope while the subject was watching a 100-second video clip. Any spike exceeding the predefined threshold is detected as a saccade event.

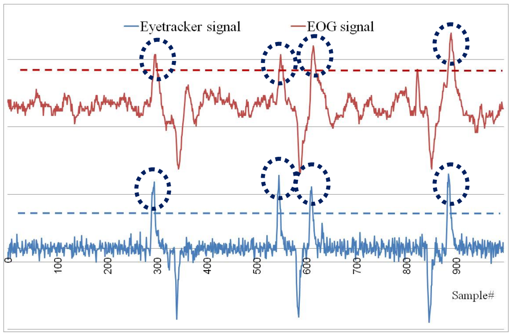


Figure 18. Horizontal eye movements recorded by eyetracker (upper) and EOG (lower). The dashed lines represent predefined thresholds. Circled spikes are reported as saccades.

Assuming the eyetracker having 100% accuracy, the experimental results from 4 subjects are listed in Table 3. The average hit rate is 63%.

Table 3: Measured EOG output for predefined saccades

Subject	JW	WW	KL	ML	Avg.
Hit rate	64.7%	70.6%	51.3%	69.2%	63.95%
Miss rate	35.3%	29.4%	48.7%	30.8%	30.05%
False alarm	17.5%	7.7%	16.7%	10.0%	9.05%

The saccade detection result is transmitted from the EOG sensor to the display by using infrared signals. On the EOG side, we used two infrared LEDs to convey the saccade direction – left or right. The LEDs are driven and controlled by amplifying the EOG signals with transistors. Either LED turns on when a saccade is sensed. On the display side, a CMOS image sensor is used to capture the infrared beam. In front of the lens of the CMOS image sensor is an IR filter to separate the meaningful signals from the background. As a result, the captured image represents the invisible infrared scene and can be used to determine the presence of infrared beams. An FPGA was programmed in Verilog to detect any pixel in the frame buffer exceeding a pre-defined threshold. Once the saccade event was detected, the display will enter the *color breakup suppressed* mode.

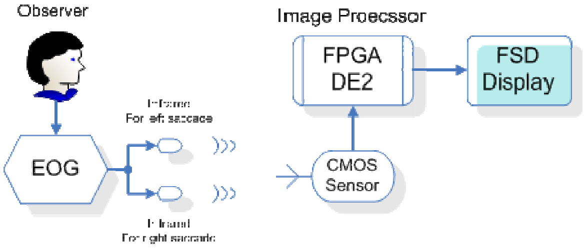


Figure 19. Block diagram of the contingent display system.

The EOG paradigm provides information of "when" color breakup is likely to happen, which is orthogonal to "how" color breakup will be suppressed. Therefore, most dynamic techniques of suppressing color breakup in literature can be applied. We chose to reduce chroma by mixing the RGB primaries [11].

To maintain the fixed luminance, the ratio between three primaries is limited by the form of

$$(\text{Red, Green, Blue}) \equiv (\alpha, \beta=(1-\alpha)/2, \gamma=(1-\alpha)/2).$$

For example, in the normal mode, the percentage of red (α) is 100%, while green (β) and blue (γ) are both 0%. If red is reduced to 80%, then both green and blue are reduced to (100%-80%)/2 = 10%. The measured color coordinates are listed in Table 4-6.

Table 4: CIE XYZ coordinates of the red primary

α, β, γ	(x,y)
(1.00, 0.00, 0.00)	(0.68, 0.32)
(0.71, 0.14, 0.14)	(0.47, 0.32)
(0.63, 0.19, 0.19)	(0.44, 0.31)
(0.56, 0.22, 0.22)	(0.41, 0.31)
(0.50, 0.25, 0.25)	(0.38, 0.31)
(0.45, 0.27, 0.27)	(0.35, 0.32)
(0.42, 0.29, 0.29)	(0.34, 0.33)
(0.38, 0.31, 0.31)	(0.31, 0.32)

Table 5: CIE XYZ coordinates of the green primary

α, β, γ	(x,y)
(0.00, 1.00, 0.00)	(0.30, 0.67)
(0.14, 0.71, 0.14)	(0.30, 0.51)
(0.19, 0.63, 0.19)	(0.31, 0.46)
(0.22, 0.56, 0.22)	(0.31, 0.42)
(0.25, 0.50, 0.25)	(0.31, 0.41)
(0.27, 0.45, 0.27)	(0.30, 0.38)
(0.29, 0.42, 0.29)	(0.30, 0.35)
(0.31, 0.38, 0.31)	(0.30, 0.33)

Table 6: CIE XYZ coordinates of the blue primary

α, β, γ	(x,y)
(0.00, 0.00, 1.00)	(0.13, 0.10)
(0.14, 0.14, 0.71)	(0.19, 0.18)
(0.19, 0.19, 0.63)	(0.22, 0.21)
(0.22, 0.22, 0.56)	(0.24, 0.23)
(0.25, 0.25, 0.50)	(0.24, 0.25)
(0.27, 0.27, 0.45)	(0.26, 0.27)
(0.29, 0.29, 0.42)	(0.27, 0.29)
(0.31, 0.31, 0.38)	(0.27, 0.29)

The measured color gamut sizes are plotted in Figure 20.

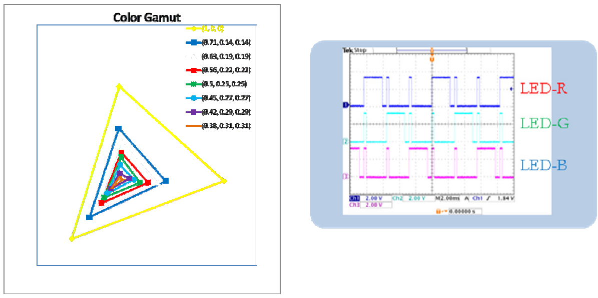


__Figure 20__. Adjustable color gamut by controlling the backlight driving patterns.

To evaluate the perceptual results, three subjects were asked to watch a black-and-white video clip (by using only the Y channel from the S-video interface). If any color was detected, then color breakup was perceived. Four different gamut sizes were used. Each gamut size was repeated for 16 times. After each trial, the subject gave a subjective rating according to the perceivable color breakup. For each subject, two sets of 16 ratings were analyzed – fixed gamut size vs. adaptive gamut size. The correlation coefficients were calculated as shown in Table 7.

Table 7: Correlation coefficients of subjective ratings between fixed and adaptive gamut size

Subject	CN	DW	JB
Correlation Coefficient	0.382	0.394	0.405

The results show that the current prototype cannot eliminate color breakup completely due to the circuit delay, but the perceived color breakup reduction is proportional to the reduced color gamut.

Conclusions

Beyond the current smart displays that optimize image quality by sensing the ambient environment, we believe that user-aware interactive display is the trend of future display technologies. After applying electro-oculogram to color breakup reduction, we are exploring the other modalities such as electroencephalogram to improve perceived image quality by sensing the user's brain activities.

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