P-03: Suppression of Color Breakup in Color-Sequential Multi-Primary Projection Displays

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Abstract
Field sequential projection displays exhibit a phenomenon of color breakup (Rainbow effect). This is considered to be a disturbing artifact with negative marketing impact. We describe the results of a psychophysical experiment comparing the visibility of the phenomenon in RGB and multi-primary displays. Surprisingly, it is found that color breakup in color sequential projection displays with five primaries is equally (for 75 Hz) or less (for 105 Hz) visible than in similar displays with three primaries (at 180 Hz), despite the lower refresh rates.

1. Objective and background
Color sequential displays create an image by dividing it in fields of the primary colors of the display and presenting those fields sequentially in time [1,2,3]. If the repetition frequency is fast enough, the eye will integrate the fields and the observer will see the original color of the image. Such displays based on DLP or LCoS technologies have been successfully introduced to the market.

Color breakup is probably the most disturbing color spatio-temporal artifact, which occurs in this type of displays. The color breakup manifests itself in the appearance of multiple color images of stationary objects during saccadic eye motion, or along the edges of moving objects when tracking the objects with the eye [4,5,6]. It is argued that since each frame is divided into different color fields, which are presented to the observer at different times, the relative motion of the eye with respect to the image causes these color fields to appear at different positions on the retina, resulting in the appearance of multiple images of different colors.

Since their first introduction to the market, the update rate of color sequential displays was increased continuously. Starting from frame rates of 60 - 80 Hz, which are typical for avoiding flicker, the rate was increased first to 120 Hz and later to 180 Hz. This increase was necessary to reduce the visibility of color breakup. Indeed, for higher frame rates the relative spatial shift of the different color fields on the retina is reduced, and as such color breakup becomes less apparent. For a three primary color sequential display, a frame frequency of 180 Hz requires a field update frequency of at least three times higher, which implies fast data rates, and more importantly, fast response of the light valve.

In multi-primary displays, more than three color-fields are used to represent the full-color image [7]. Therefore at first glance, higher data rates and even faster light valve response times may be required in order to build color sequential multi-primary displays. A question arises whether a multi-primary display, which due to response time limitation, will operate at a relatively low frame rate compared to RGB display, would be acceptable.

The aim of the current work is to investigate the effect of having more than 3 primaries on color breakup, and to determine the level of color breakup as a function of frame rate in a multi-primary system as compared to a three-primary system. The present paper describes the results of this experiment. It is found that color breakup is highly reduced in multi-primary displays even at lower frame frequencies.

2. Experimental setup
The experiment included 21 participants, 18 men and 3 women. Their ages ranged between 20 and 40. All participants had normal vision as was tested with an Ishihara test for color deficiency and on the Landolt C-scale for acuity. Before the start of the experiment participants got an explanation of the phenomenon of color breakup, and were trained to detect color breakup on a black & white block pattern. All subjects were well able to see color breakup for such a pattern.

A three-primary (RGB) LCoS projection display (52” Philips Cineos) operating with a frame frequency of 180 Hz and two five-primary displays (modified 52” Philips Cineos sets with RGBYC primaries) operating at variable frame frequencies (75, 85 or 105 Hz) were placed side by side, directed towards the viewer who sat about 3 m from each display. The middle set was the normal three-primary LCoS and always played at 180 Hz. One of the other two multi-primary sets always played at 105 Hz and the other played at either 85 or 75 Hz. The position of the 105 Hz set was switched between the left and the right for different subjects. The peak-white luminance of each display was set to about 450 cd/m^2. Custom-built video streamers were used to play the same content (1280x720 HD at 60 Hz) to all three displays. Six different scenes were used to perform the test (Awards, Angel, Subtitles, Nature, Monsters, and Gladiator). Participants got a questionnaire with three questions, which they had to answer for each scene and for each of the two different combinations of refresh rates. The first question was to rank the three displays on the amount of color breakup. In the second one, they had to indicate for each set the visibility of color breakup on a three-point scale (none, some, lots). In the third question, they were asked to indicate for each set if they would buy it or not on a four-point scale (yes, probably yes, probably no, no).

The rankings of all viewers were converted via a paired comparison to quality scale values [8]. The least preferred display was set to 0. The distance between the marks indicates how much one display is preferred over the other. In general, these differences cannot be related exactly to a percentage of preference, but in this experiment differences of 0.5, 1, and 2 between set A and B correspond approximately to a preference of about 60 - 70%, 80 – 90%, 95 – 100%, respectively, for set A over set B.

3. Results

Figure 1 shows the results of the ranking test on color breakup visibility averaged across all video content shown. The upper panel shows a comparison between the three-primary (RGB) display at 180 Hz and two multi-primaries displays running at 75 and 105 Hz respectively. In the lower panel the RGB display (again at 180 Hz) is compared with multi-primary displays running at 85 and 105 Hz respectively. The light gray line between the marks indicates a statistically significant difference, while the dark gray line indicates a non-significant difference.

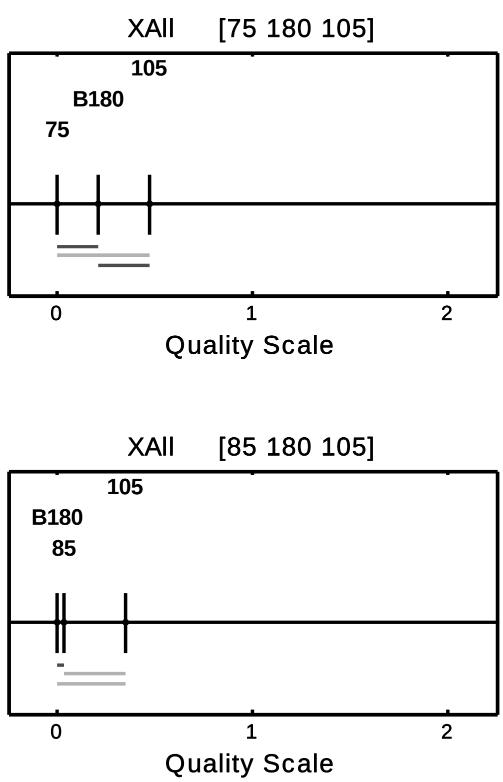

Figure 1: Ranking results collapsed across scenes for a three primary display at 180 Hz, a five primary display at 105 Hz and one at 75 Hz (upper panel) and 85 Hz (lower panel).

The results show that for the visibility of color breakup the five-primary displays are either equally (for a frame frequency of 75 and 85 Hz) or more (for a frame frequency of 105 Hz) preferred than the conventional three-primary display, which runs at a much higher frame frequency of 180 Hz. This general trend was found in four of the six scenes.

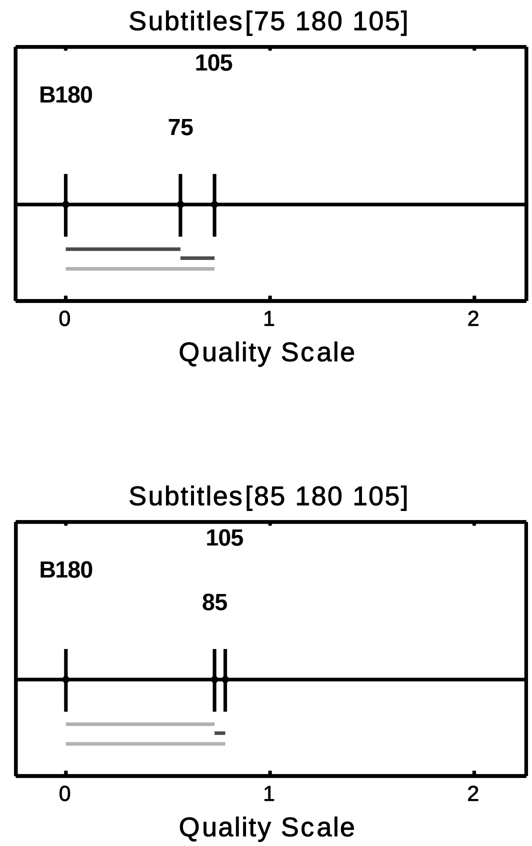

Figure 2: Same as Figure 1, but only for “Subtitles” image.

For the scene “Subtitles”, the results were much different as illustrated in Figure 2. This scene, the credits at the end of a film, consists of scrolling white text on a black background, and differs from the other scenes because of its high color breakup visibility (see also Fig. 3). For this scene, both the 85 and 105 Hz five-primary displays were significantly preferred over the three-primary display. Even the 75 Hz five-primary display was more preferred than the conventional three-primary display, but this difference was not statistically significant.

The results of the amount of visible color breakup (i.e. the scores on the second question of the questionnaire) are shown in figure 3. It shows that color breakup in all remaining scenes was much less noticeable than in the scene “Subtitles”. The variance in the amount of color breakup in the other scenes suggests that contrast in either luminance or color saturation (highly saturated objects surrounded by low saturated background, e.g. deep red dress in the midst of black tuxedoes in the “Awards” scene) is the primary contributor for the visibility of this phenomenon (Table 1). The relation between contrast and color breakup visibility, however, needs further investigation, because although it is clear that color breakup visibility is scene dependent, it may be argued that this dependency is attributed to content rather than image attributes - e.g. the eye's tendency to track faces (regardless of contrast or color) creates increased saccadic motion.

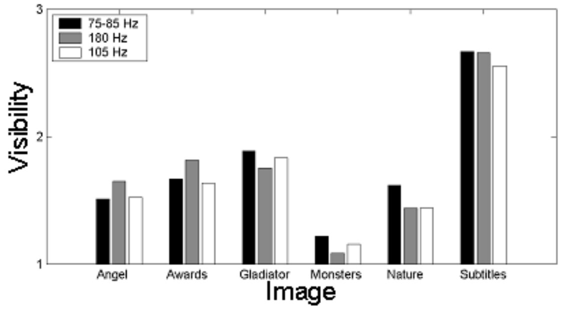

Figure 3: Visibility of color breakup (1=none, 2=some, 3=lots) per scene collapsed across subjects.

Scene	Motion	Contrast	Color saturation	General characteristics
Awards	slow	medium	low / high	outdoors, faces
Angel	medium	high	low	indoors
Subtitles	medium	high	none	film credits
Nature	slow	low	low	high-key
Monsters	medium - fast	low	high	fuzzy, synthetic colors
Gladiator	fast	high	low	action scene

Table 1: Description of scenes and their dominant image attributes.

The results of the third question of the questionnaire are summarized in figure 4. It shows that visibility of color breakup

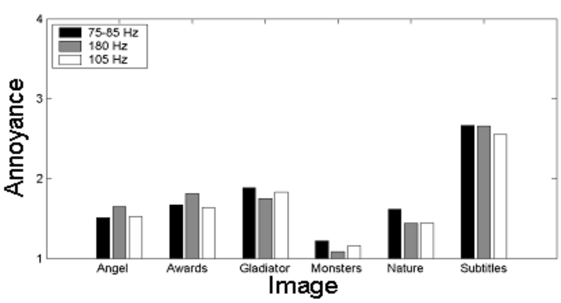

Figure 4: Annoyance of color breakup for each of the six images for a three-primary display at 180 Hz and five-primary displays at 105 Hz and 75 - 85 Hz. Annoyance was directly related to the question if people would buy a TV set with amount of color breakup shown (1=yes, 2=probably yes, 3=probably no, 4=no).

does not seem to have a significant effect on the readiness to buy a TV. Most scores are distributed between "Yes" and "Probably yes" with the exception of the scene "Subtitles". For this particular scene, the readiness to buy a TV with this scene shown varies between "Probably yes" and "Probably no".

4. Model

The most disturbing scene in our experiment was "Subtitles", a moving white text on a black background. We initially assumed that the color breakup in this scene was related to the motion of the text. A simple calculation, however, shows that in the time scale of a single color field (~ 2 ms) the maximum shift between color fields is less than a pixel (for a 1280 x 720 display and a few seconds for the text scrolling across it), and thus, is not expected to be detectable. As a consequence, the color breakup seen in our experiments should probably be attributed to saccadic eye motion, which may have speeds up to 300^{o}/sec. This results in a shift of ~0.6^{o} during a color field period, corresponding to a shift of 3 cm (or equivalently 30 pixels on a 55" screen) at 3 m viewing distance, a shift which is clearly seen. Hence the increased visibility of color breakup in the "Subtitles" scene is not expected to be a consequence of the text motion, but rather of the high contrast between the white text and the black, clutter free background. In that case, a similar level of visible color breakup can be expected from a still image containing the same text. This should be verified in further experiments.

To further study the effect of color breakup, we have tried to examine a simplified model. We start with a static image of a white strip on a black background. We assume that the eye performs saccadic motion in a constant speed, and that the color fields are shifted, one with respect to the other, accordingly. We further assume that the eye tracks the brightest field (green in the RGB display and yellow in the five-primary display). Each of the primary color fields is split into three channels, a luminance channel and red-green and yellow-blue opponent channels, each of which is filtered spatially with the corresponding response. For the five-primary display, we use the measured XYZ values to calculate the luminance and opponent signals, while for the RGB display we use the same chromaticity of the five-primary RGB components, and adjust the relative luminance levels to obtain equal white points at equal brightness. We then 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 weaker 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 (with an amplitude slightly larger than that observed in the RGB display). This is consistent with the observation that red and green shadows are seen in RGB displays, while for the five-primary display 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 color breakup. The modulation amplitude is weaker in the case of the five-primary display due to the reduced variation in luminance between the fields and the stronger spatial filtering of the blue-yellow channel in respect to that of the red-green channel. Thus, the yellow shadow on one edge tends to merge with the white stripe while the blue shadow on the other edge merges with the black background. This is probably due to the suppression of the color contrast by the limited spatial response, and the low luminance contrast (between yellow and white, and between black and blue).

5. Discussion

The results indicate that five-primary displays produce less color breakup than three-primary displays even at lower frame rates. For three-primary displays the color breakup is directly related to the refresh rate; the lower the refresh rate the larger the time of each color field the more visible it becomes [4,5,6]. Therefore, high frame frequency of 180 Hz is used to avoid color breakup. Yet, in the five-primary sets not only the frame frequency is smaller, but also the field frequency (i.e. the frame frequency times the number of fields) is lower. For a 3-primary system at 180 Hz the field frequency is 3x180 Hz = 540 Hz, whereas for a 5-primary system at 105 Hz, the field frequency is 5x105 Hz = 525 Hz. Thus, in the 5-primary display each color field is presented for a longer time, and so, is expected that color breakup will be more visible. Since the opposite is true, there is clearly a second parameter, apart from the refresh rate, that determines the visibility of color breakup.

At this moment, we can only hypothesize about the reasons for the reduced visibility of color breakup in multi-primary displays. The model described in section 4 above is an attempt to understand the additional parameters that affect color breakup in multi-primary displays. In addition, we suggest that the use of spectrally wide yellow and cyan primaries capable of exciting two types of cones simultaneously (in contrast to the RGB primaries which excite mostly one type of cone) may be another reason for the better performance of the multi-primary display.

Another reason may be attributed to the characteristics of cone saturation [9]. The pulsed stimulus produced by the sequential exposure of the fovea generates a strong surge of neural responses, which, in the absence of a steady field to act as an inhibitory effect, brings the cones closer to, or beyond their saturation threshold. In this experiment, the pulse stimulus produced by the five-primary display is lower in its intensity in comparison to that produced by the RGB display.

These hypotheses will be further investigated in the coming months. Overall, we can conclude that our results imply that multi -primary displays may use light valves with similar or even lower response times than three-primary displays. The results also show that for the frame rates tested, color breakup was visible to some extent, yet it hardly affected the readiness to buy such a TV set.

6. Acknowledgements

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7. References

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