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Comparing levels of crosstalk with red/cyan, blue/yellow, and green/magenta anaglyph 3D glasses

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ABSTRACT

The Anaglyph 3D method of stereoscopic visualization is both cost effective and compatible with all full-color displays, however this method often suffers from poor 3D image quality due to poor color quality and ghosting (whereby each eye sees a small portion of the perspective image intended for the other eye). Ghosting, also known as crosstalk, limits the ability of the brain to successfully fuse the images perceived by each eye and thus reduces the perceived quality of the 3D image. This paper describes a research project which has simulated the spectral performance of a wide selection of anaglyph 3D glasses on CRT, LCD and plasma displays in order to predict ghosting levels. This analysis has included for the first time a comparison of crosstalk between different color-primary types of anaglyph glasses - green/magenta and blue/yellow as well as the more traditional red/cyan. Sixteen pairs of anaglyph 3D glasses were simulated (6 pairs of red/cyan glasses, 6 pairs of blue/yellow glasses and 4 pairs of green/magenta glasses). The spectral emission results for 13 LCDs, 15 plasma displays and one CRT Monitor were used for the analysis. A custom written Matlab program was developed to calculate the amount of crosstalk for all the combinations of different displays with different anaglyph glasses.

Keywords: stereoscopic, 3D, anaglyph, crosstalk, ghosting

1. INTRODUCTION

The anaglyph method of displaying stereoscopic 3D images relies on the multiplexing of left and right perspective views into complementary color channels of the display - the viewer then wears a pair of glasses containing color filters which intend to only pass the appropriate color channels for each eye (e.g. the red channel to the left eye and the blue and green channels to the right eye for the most common red/cyan anaglyph process), and therefore the correct perspective images for each eye. The anaglyph method has existed since 1853[1] and remains a common 3D display technique today because it works with any full-color display, is easy to encode images into anaglyph format, and the glasses are relatively cheap to produce. Unfortunately the anaglyph 3D method often suffers from relatively poor 3D image quality due to its inability to accurately display full-color 3D images, and commonly the presence of relatively high levels of 3D crosstalk.

The terms ghosting and crosstalk with respect to stereoscopic displays are often used interchangeably however we will use the definition by Lipton[2] in this discussion: Crosstalk is the "incomplete isolation of the left and right image channels so that one leaks or bleeds into the other - like a double exposure. Crosstalk is a physical entity and can be objectively measured, whereas ghosting is a subjective term" and refers to the "perception of crosstalk". We have used the following mathematical definition of crosstalk: crosstalk (%) = leakage / signal × 100 (where leakage is used here to mean the raw leakage of light from the unintended channel to the intended channel).

Anaglyph 3D encoding can be performed using any pair of complementary color channels to store the left and right perspective images. Red/cyan has traditionally been the most common choice of colors for anaglyph glasses, however recently blue/yellow and green/magenta color combinations have also been used widely.

Figure 1 graphically illustrates the principle behind the image separation used in anaglyphic image viewing, as well as the concept of crosstalk (ghosting or leakage) and signal (intended image). The display has a specific spectral output for each of the red, green and blue sub-pixels (color channels). With red/cyan glasses, the left image is stored in the red color channel, while the right image is stored in the cyan (green + blue) color channel. The red/cyan lenses in the glasses have

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a specific spectral transmission response such that red filter predominantly transmits light from the red color channel while blocking light from the blue and green color channels (and vice versa for the other eye). Due to the imperfect nature of the spectral performance of the filters and the spectral emission of the color channels of the display, some of the right image will be visible to the left eye (and vice versa for the other eye) and this is referred to as leakage or crosstalk.

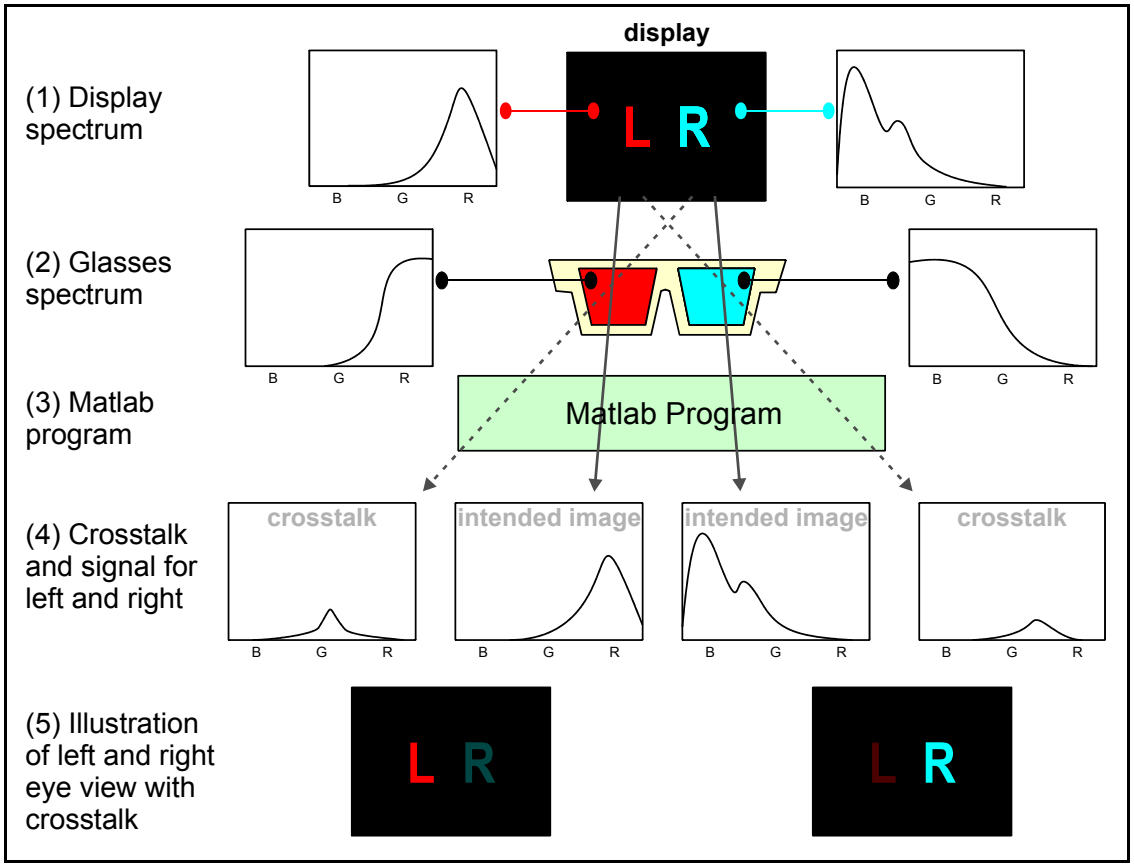

Figure 1: Illustration of the process of anaglyph spectral ghosting and its simulation in this project. From the top: (1) Spectral response of display, (2) spectral response of anaglyph glasses, (3) simulation of crosstalk using a computer program, (4) spectral output characteristic of crosstalk and intended image, and (5) visual illustration of left eye and right eye view with crosstalk.

This paper carries on from the work of Woods and Rourke[3], and Woods, Yuen and Karvinen[4] which considered red/cyan anaglyph crosstalk of various displays and developed an algorithm to estimate the amount of 3D crosstalk that will be present when a particular pair of anaglyph glasses is used to view an anaglyph 3D image on a particular full-color display. Past studies by the authors have also examined the sources of crosstalk in time-sequential 3D displays[5,6,7,8,9]. This paper extends the developed algorithms and examines and compares the levels of crosstalk present between different color-primary types of anaglyph glasses (i.e. red/cyan, blue/yellow and green/magenta) with different displays.

It should be noted that this paper only examines and compares crosstalk in anaglyph images and does not examine other aspects of 3D image quality (including psychological effects). This aspect should be considered closely when reviewing the results of this paper, and is discussed in more detail in Section 4.2.

2. EXPERIMENTAL METHOD

Firstly, the spectral output of a large selection of displays has been measured using a manually calibrated Ocean Optics USB2000 spectroradiometer as part of this and previous studies[3,4]. Table 1 lists the displays sampled - comprising 13 LCD monitors, 15 plasma-display panels (PDPs), and one CRT (Cathode Ray Tube) monitor.

Table 1: Listing of all the displays simulated in this particular study.

Display ID	Display Make and Model
LCD01	Samsung SynchMaster 171s
LCD02	Benq FP731
LCD03	NEC MultiSync LCD 1760V
LCD04	Acer AL1712
LCD05	Acer FP563
LCD06	Benq FP71G
LCD07	Benq FP71G+S
LCD08	Philips 150S3
LCD09	Hewlett Packard HPL1706
LCD11	Samsung SyncMaster 740N
LCD12	Philips 190s
LCD13	Samsung SyncMaster 913B
LCD14	ViewSonic VX922
PDP01	LG DT-42PY10X
PDP02	Fujitsu P50XHA51AS
PDP03	NEC PX-50-XR5W
PDP04	Panasonic TH-42PV60A
PDP05	Samsung PS-42C7S
PDP06	LG RT-42PX11
PDP07	NEC PX-42XM1G
PDP08	Sony PFM-42V1
PDP09	Sony FWD-P50X2
PDP10	Hitachi 55PD8800TA
PDP11	Hitachi 42PD960BTA
PDP12	Pioneer PDP-507XDA
PDP13	Pioneer PDP-50HXE10
PDP14	Fujitsu PDS4221W-H
PDP15	Samsung PS50A450P1DXXY
CRT	Mitsubishi Diamond View VS10162

NB: Due to manufacturing variation or experimental error, the results in this paper should not be considered representative of all displays of that particular brand or model.

Secondly, the spectral transmission of a large selection of anaglyph glasses were collated - using a Perkin Elmer Lambda 35 spectrophotometer to measure newly acquired anaglyph 3D glasses and re-measure some older glasses, as well as using spectral data for anaglyph glasses from a previous study[4]. Spectral data for more than 70 pairs of anaglyph glasses have now been sampled, however, only 16 pairs are reported here for the sake of brevity (6 red/cyan, 6 blue/yellow, and 4 green/magenta). Table 2 lists the anaglyph glasses described in this study. Most of the glasses reported here consist of gel-type filters in a cardboard frame - the exceptions are 3DG70, 71 and 72 which are glass dichroic filters. Although at the time of this study we did not possess a physical sample of the dichroic filters, the spectral transmission curves of the filters were available and have been included in the simulations for comparison purposes. Another exception is 3DG28 which is a set red and cyan filters printed using a Canon inkjet printer onto transparency film – again, included for comparison purposes. The red/cyan glasses 3DG4, 32, 73 and 74 were chosen because of their good performance. The blue/yellow glasses 3DG22, 23, 51, 67, 69 and green/magenta glasses 3DG68, 75, 76 were chosen because they were the only samples of those color-type of anaglyph glasses that were able to be obtained by the authors for testing.

Table 2: Listing of all the anaglyph glasses simulated in this particular study.

Glasses ID	Color of Single Primary Filter	Color of Double Primary Filter	Description
3DG4	Red	Cyan	Sports Illustrated - MFGD By Theatric Support
3DG22	Blue	Yellow	Stereospace - SpaceSpex™ - 3DTV Corp
3DG23	Blue	Yellow	ColorCode 3.D. (Black/Grey cardboard Frame - no arms)
3DG28	Red	Cyan	Red/Cyan Canon Inkjet Printer Transparency
3DG32	Red	Cyan	World 3-D Film Expo (3D DVD) - "Real 3D" - SabuCat Productions
3DG51	Blue	Yellow	Ghosts of the Abyss (3D DVD) - Geneon Entertainment
3DG67	Blue	Yellow	ColorCode 3.D. (Blue Frame)
3DG68	Green	Magenta	Journey to the Centre of the Earth (3D DVD) - TrioScopics, LP
3DG69	Blue	Yellow	Monsters vs. Aliens - NBC - Intel - ColorCode 3D (Superbowl 2009)
3DG70	Red	Cyan	Edmund Optics Dichroic Filters - red U52-528, cyan U52-537
3DG71	Blue	Yellow	Edmund Optics Dichroic Filters - blue U52-531, yellow U52-543
3DG72	Green	Magenta	Edmund Optics Dichroic Filters - green U52-534, magenta U52-540
3DG73	Red	Cyan	3D Vision Discover - NVIDIA
3DG74	Red	Cyan	Stereoscopic Displays and Applications - American Paper Optics
3DG75	Green	Magenta	My Bloody Valentine (3D DVD) - LionsGate - Trioscopics LP
3DG76	Green	Magenta	Coraline (3D DVD) - LAIKA - Trioscopics LP

PLEASE NOTE: Generally only a single pair of glasses of each particular style/brand was sampled. As such, due to manufacturing variations or experimental error, the results provided in this paper should not be considered to be representative of all glasses of that particular style/brand.

The third step was to use a custom written Matlab[10] program to calculate the amount of crosstalk in anaglyph images for different display, glasses, and color-primary combinations. With reference to Figure 1, the program first loads and resamples the display and glasses spectral data so that all data is on a common x-axis coordinate system. For each lens of the glasses, the program multiplies the spectrum of the display color channel(s) which match the lens with the spectrum of that lens to obtain the intended image curve for each eye. To obtain the crosstalk curve for each eye, the spectrum of the lens is multiplied by the spectrum of the color channel(s) which should not pass through that lens. Where the spectrum of two display color channels need to be combined for the calculation (e.g. cyan = blue + green) the two color spectrums are added before multiplying with the lens spectrum. For example: red signal curve = red lens spectrum multiplied by red display spectrum, and red crosstalk curve = red lens spectrum multiplied by the addition of the green display spectrum and the blue display spectrum. The program also scales these results curves to include the human-eye sensitivity to different wavelengths of light[11] (see Figure 2). The crosstalk percentage for each eye is then calculated by dividing the area under the crosstalk curve by the area under the intended signal curve for each eye and multiplying by 100. The overall crosstalk factor for a particular pair of glasses when used in combination with a particular display is the sum of the left- and right-eye percentage crosstalk values. It should be noted that the overall crosstalk factor is not a percentage, but rather a number that allows the comparison of different glasses/display combinations. The program automates the process of performing a cross comparison of all the displays against all of the glasses.

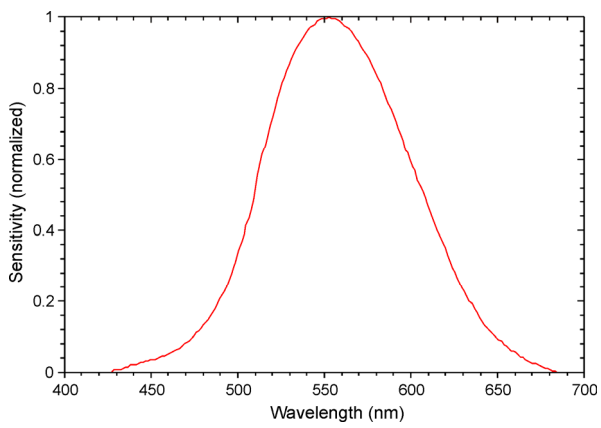

Figure 2: CIE 1931 photopic human eye response.

3. RESULTS

3.1 Anaglyph 3D Glasses Spectral Transmission

The spectral results for the anaglyph glasses analyzed in this paper are shown in Figures 3 through 8. It can be seen in all cases that the dichroic filters have a high-transmittance pass-band, a very low-transmittance stop-band, and generally

a very sharp transition. It can be seen that the inkjet filters in Figures 3 and 4 have very poor performance in the stop band which will negatively affect their use as anaglyph filters considerably. The remaining curves in Figures 3 through 8 are gel-filters and although there is some clustering, it can be seen that can be a lot of variation between individual filters.

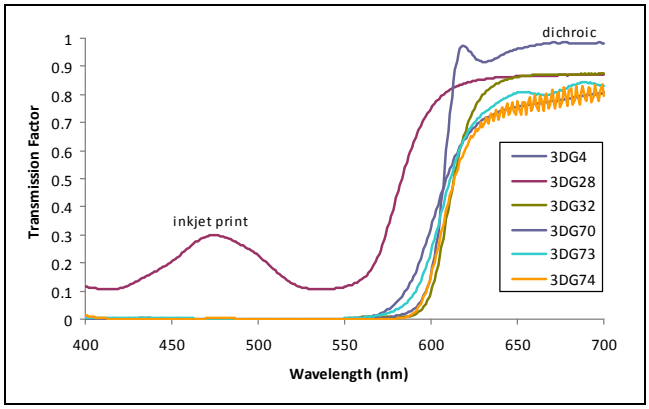

Figure 3 - Spectral transmission of the red filters.[α]

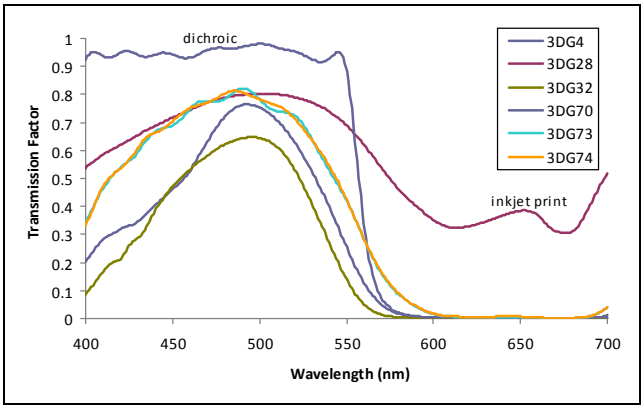

Figure 4 - Spectral transmission of the cyan filters.

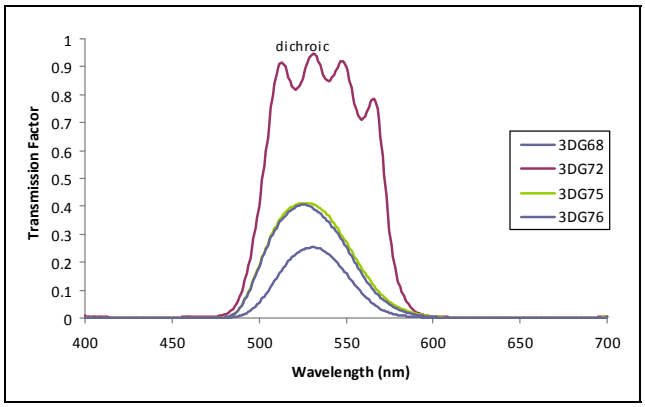

Figure 5 - Spectral transmission of the green filters.

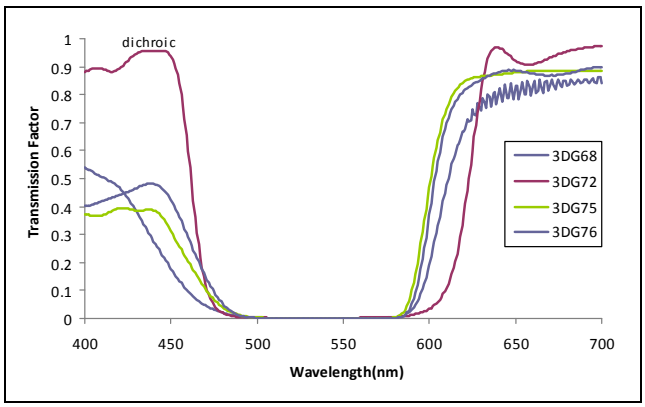

Figure 6 - Spectral transmission of the magenta filters.

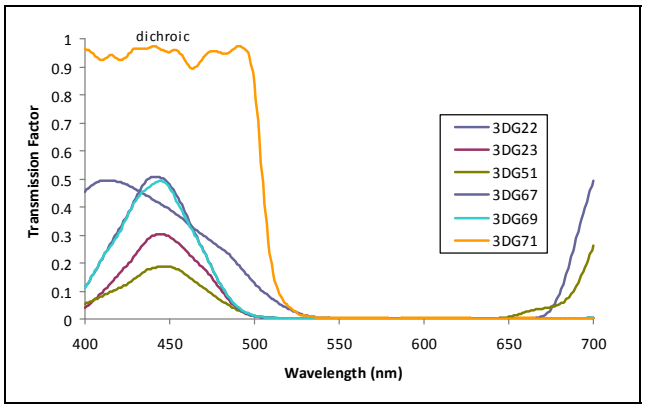

Figure 7 - Spectral transmission of the blue filters.

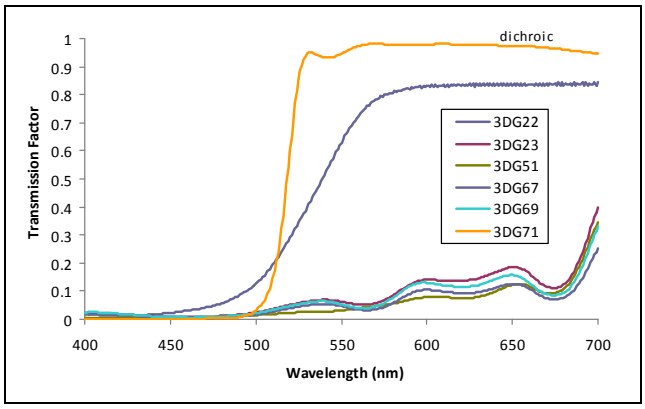

Figure 8 - Spectral transmission of the yellow filters.

[α] The legends and colors of some of the figures and tables in this paper won't be distinguishable when printed in black and white. A color version of the figures and tables is available from the primary author's website.

3.2 Display Device Spectral Emission

The spectral emission measurements of the 29 different displays reported in this study (13 LCD monitors, 15 plasma displays, and one CRT monitor) are shown in Figures 9 through 11.

Figure 9 shows the spectral output of all the tested LCD monitors. All of the LCD monitors tested used CCFL (Cold Cathode Fluorescent Lamp) backlights and the spectral peaks of the light output by the backlight are clearly visible. There is a lot of similarity between the spectral characteristics of all the LCD monitors, however, some differences are evident in the out-of-band rejection (e.g. the amount of green light present in the red color primary) which will be related to the quality of color filters used for each of the color primaries.

Figure 10 shows the spectral output of all the tested plasma displays. The color spectrum of the red and blue color primaries are very similar across all the tested plasma displays, however, there is a lot of variation of the spectral response of the green color primary which will probably relate to the formulation of the phosphors used.

Figure 11 shows the spectral output of an example CRT monitor. A previous paper by Woods and Tan[5] reported that 11 tested CRT monitors had almost exactly the same spectral response which suggests that most CRTs use the same phosphor formulation for each of the color primary channels. It is believed that this graph can therefore be considered representative of most CRTs.

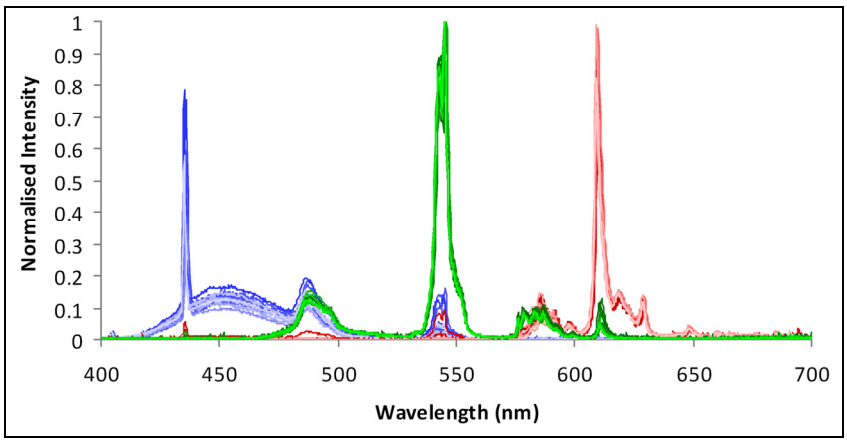

Figure 9: Color spectrum of the tested LCD monitors

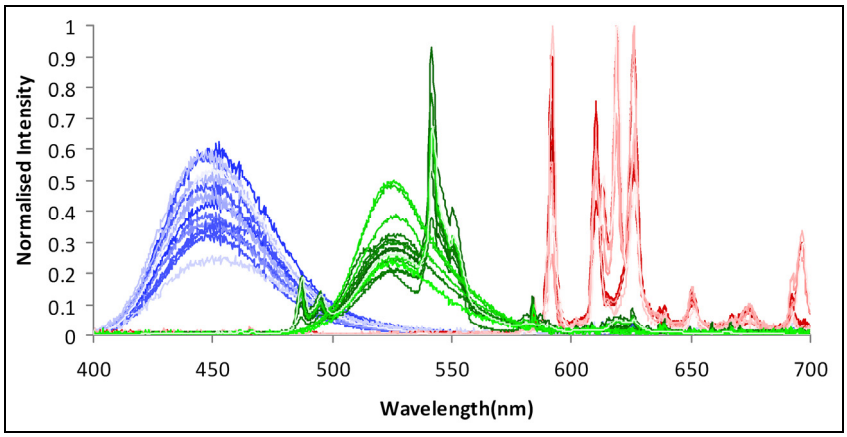

Figure 10: Color spectrum of the tested plasma displays

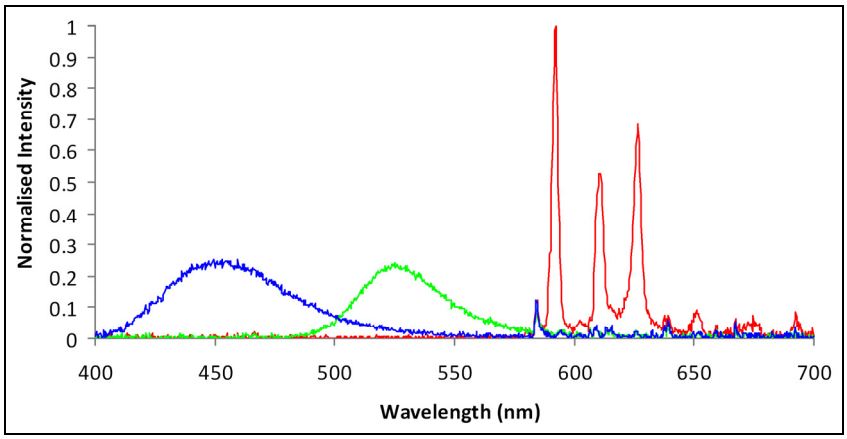

Figure 11: Color spectrum of an example CRT monitor

3.3 Crosstalk Calculation Results

The crosstalk results as calculated by the Matlab crosstalk calculation program for the combination of all displays against all anaglyph glasses are shown in Table 3 and 4. For each display/glasses combination the table lists the percentage crosstalk for the single-color-primary eye (top cell), the percentage crosstalk for the double-color-primary eye (middle cell), and the overall crosstalk factor for both eyes combined (bottom cell). The overall crosstalk factor is the sum of the

left and right eye percentages, and as such is not a percentage. To aid in the analysis of the tables, some of the overall crosstalk factors have been tagged/highlighted.

Table 3: Crosstalk calculation results for the LCD and CRT monitors. (The lowest overall crosstalk factors for each display have been highlighted in bright green and tagged with a '#' character, and the highest overall crosstalk factors are highlighted in orange and tagged with a '+' character. Overall crosstalk factors of less than 15 have been highlighted in light green - this threshold figure does not have any significance apart from allowing us to highlight the lower overall crosstalk factor results.)

		Displays													
Glasses		LCD1	LCD2	LCD3	LCD4	LCD5	LCD6	LCD7	LCD8	LCD9	LCD11	LCD12	LCD13	LCD14	CRT
3DG4	Red	16.1	14.5	16.0	18.1	22.3	13.1	16.6	22.9	15.4	12.8	15.5	14.0	12.9	26.8
	Cyan	0.8	0.8	0.5	7.7	2.5	0.7	0.9	1.4	1.5	1.3	1.1	0.3	0.6	4.9
	Overall	16.9	15.2	16.5	25.8	24.8	13.8	17.5	24.3	16.9	14.2	16.6	14.3	13.5	31.7
3DG22	Blue	65.5	68.7	72.0	70.9	59.0	110.2	78.6	55.8	67.9	90.6	89.1	68.4	65.9	129.5
	Yellow	3.9	3.1	3.0	6.1	10.0	1.9	3.0	8.7	4.8	2.9	2.3	2.3	4.2	4.5
	Overall	69.4	71.9	75.0	77.0	69.1	112.1	81.6	64.5	72.7	93.5	91.4	70.6	70.1	**134.0**$^{+}$
3DG23	Blue	26.0	23.3	28.7	32.5	27.0	40.8	28.2	24.6	25.8	34.5	32.1	24.8	26.3	30.3
	Yellow	4.2	3.4	3.2	6.3	9.8	2.1	3.2	8.6	5.0	3.1	2.4	2.6	4.5	5.1
	Overall	30.2	26.7	31.9	38.7	36.8	42.9	31.4	33.2	30.8	37.6	34.5	27.4	30.8	35.4
3DG28 (inkjet)	Red	92.2	84.0	78.3	96.5	87.1	70.4	85.2	87.6	73.9	70.7	75.1	90.2	81.4	108.5
	Cyan	14.6	15.0	15.7	19.6	18.1	17.2	15.5	17.2	18.9	17.4	17.8	13.1	14.6	16.9
	Overall	**106.8**$^{+}$	**99.0**$^{+}$	**94.0**$^{+}$	**116.1**$^{+}$	**105.2**$^{+}$	87.7	**100.7**$^{+}$	**104.7**$^{+}$	**92.8**$^{+}$	88.1	92.9	**103.3**$^{+}$	**96.0**$^{+}$	125.4
3DG32	Red	8.8	8.1	11.0	9.9	15.6	8.2	10.1	16.7	10.9	8.1	9.9	7.6	7.1	18.1
	Cyan	0.6	0.7	0.5	7.5	2.3	0.6	0.8	1.3	1.3	1.3	1.0	0.2	0.5	4.7
	Overall	9.4	8.8	11.5	**17.4**$^{\#}$	18.0	8.8	10.9	18.0	12.2	9.4	10.9	7.8	7.6	22.8
3DG51	Blue	33.6	31.4	37.3	39.5	33.7	54.1	37.1	31.3	34.2	44.9	42.9	32.3	34.1	40.2
	Yellow	4.0	3.4	3.1	5.7	8.8	2.0	3.2	7.8	4.9	3.1	2.5	2.5	4.2	5.2
	Overall	37.6	34.8	40.4	45.3	42.5	56.1	40.3	39.1	39.1	48.0	45.4	34.9	38.3	45.4
3DG67	Blue	22.8	19.8	25.0	28.9	24.2	34.6	24.2	22.0	22.8	29.4	28.0	21.3	22.8	27.1
	Yellow	4.3	3.4	3.3	6.4	10.1	2.1	3.2	8.9	5.0	3.1	2.4	2.6	4.5	5.1
	Overall	27.07	23.2	28.2	35.3	34.2	36.7	27.4	30.9	27.9	32.5	30.4	23.9	27.4	32.2
3DG68	Green	7.7	5.5	5.9	20.6	23.3	4.0	5.2	19.0	9.1	5.0	4.2	4.0	7.8	10.9
	Magenta	8.9	7.5	11.0	10.4	14.4	8.2	9.0	15.5	8.2	6.8	9.2	7.7	6.7	14.1
	Overall	16.6	12.9	16.9	31.0	37.7	12.2	14.2	34.5	17.3	11.7	13.4	11.7	14.4	24.9
3DG69	Blue	24.3	21.3	26.5	30.3	25.4	37.0	25.7	23.1	24.2	31.2	29.7	22.7	24.2	28.7
	Yellow	4.2	3.4	3.2	6.2	9.8	2.1	3.2	8.7	5.0	3.1	2.4	2.6	4.4	5.1
	Overall	28.5	24.7	29.8	36.6	35.2	39.1	28.9	31.7	29.2	34.2	32.1	25.2	28.7	33.8
3DG70 (dichroic)	Red	8.6	7.7	10.9	9.9	15.4	8.0	9.5	16.0	9.7	7.6	9.3	7.1	6.7	18.3
	Cyan	0.6	0.6	0.4	7.7	2.3	0.6	0.7	1.1	1.2	1.1	0.9	0.2	0.4	5.0
	Overall	**9.2**$^{\#}$	**8.3**$^{\#}$	**11.3**$^{\#}$	17.7	**17.7**$^{\#}$	**8.6**$^{\#}$	**10.2**$^{\#}$	**17.1**$^{\#}$	**10.8**$^{\#}$	**8.6**$^{\#}$	**10.2**$^{\#}$	**7.3**$^{\#}$	**7.1**$^{\#}$	23.4
3DG71 (dichroic)	Blue	71.1	80.2	81.1	77.8	65.7	128.2	90.5	61.4	75.5	105.9	101.3	76.7	72.7	122.4
	Yellow	3.6	2.8	2.7	6.2	10.8	1.7	2.7	9.3	4.6	2.6	2.0	1.9	4.1	4.0
	Overall	74.7	83.0	83.8	84.0	76.4	**129.9**$^{+}$	93.3	70.7	80.1	**108.5**$^{+}$	**103.3**$^{+}$	78.6	76.8	126.4
3DG72 (dichroic)	Green	8.5	6.1	6.4	20.8	23.7	4.4	6.0	19.8	10.3	5.6	5.1	4.5	8.2	11.6
	Magenta	6.0	5.3	8.8	6.4	10.5	6.5	7.5	13.0	8.2	6.1	8.5	6.4	5.1	10.0
	Overall	14.5	11.4	15.2	27.2	34.2	11.0	13.4	32.9	18.5	11.8	13.7	10.9	13.4	**21.6**$^{\#}$
3DG73	Red	14.1	12.7	14.7	15.8	20.5	11.7	14.7	21.2	14.3	11.5	13.9	12.2	11.3	24.0
	Cyan	1.9	1.7	1.4	8.5	3.7	1.7	1.9	2.6	2.9	2.1	2.3	1.1	1.4	5.7
	Overall	16.0	14.4	16.0	24.2	24.1	13.4	16.6	23.7	17.3	13.6	16.2	13.3	12.6	29.7
3DG74	Red	8.6	7.9	10.9	9.9	15.7	8.0	9.8	16.6	10.4	7.8	9.6	7.3	6.9	18.5
	Cyan	1.9	1.8	1.4	8.5	3.7	1.7	2.0	2.6	3.0	2.2	2.3	1.1	1.4	5.7
	Overall	10.5	9.7	12.3	18.4	19.4	9.7	11.8	19.2	13.4	10.0	12.0	8.4	8.3	24.2
3DG75	Green	9.4	6.7	7.2	21.9	25.0	5.0	6.4	20.8	10.8	6.0	5.4	5.0	9.0	11.9
	Magenta	10.4	8.7	12.0	12.2	16.0	9.2	10.2	16.7	8.9	7.6	10.2	8.8	7.8	17.1
	Overall	19.8	15.4	19.2	34.1	41.0	14.2	16.6	37.5	19.6	13.6	15.6	13.8	16.7	29.0
3DG76	Green	9.2	6.6	7.1	21.9	25.0	4.9	6.2	20.7	10.6	5.9	5.3	4.9	8.9	11.8
	Magenta	9.0	7.5	11.1	10.6	14.6	8.3	9.0	15.5	8.0	6.8	9.2	7.7	6.8	15.5
	Overall	18.3	14.1	18.2	32.5	39.6	13.2	15.3	36.2	18.6	12.7	14.4	12.6	15.7	27.3

Key: Overall Crosstalk Factor: **00.0**$^{+}$ = Highest, **00.0**$^{\#}$ = Lowest, 00.0 = Less than 15.

Table 4: Crosstalk calculation results for the PDP monitors.

Glasses		Displays														
		PDP1	PDP2	PDP3	PDP4	PDP5	PDP6	PDP7	PDP8	PDP9	PDP10	PDP11	PDP12	PDP13	PDP14	PDP15
3DG4	Red	14.9	24.8	9.8	15.6	10.9	17.9	13.6	16.9	16.7	12.8	11.1	8.4	10.2	16.5	13.5
	Cyan	1.1	1.0	2.1	2.4	2.1	1.5	1.3	2.2	1.2	2.8	1.6	1.4	1.9	1.5	0.7
	Overall	16.0	25.8	11.9	17.9	13.0	19.4	14.9	19.1	17.9	15.7	12.7	9.8	12.1	18.0	14.2
3DG22	Blue	72.3	49.4	78.2	73.8	54.7	72.2	68.5	60.1	59.1	59.9	57.7	88.9	70.7	61.9	54.6
	Yellow	2.9	5.9	3.8	3.5	4.7	3.5	7.3	6.4	4.1	6.2	6.6	3.6	4.8	10.8	3.5
	Overall	75.3	55.2	**82.0**$^{+}$	77.3	59.5	75.7	75.8	66.6	63.2	66.1	64.3	**92.5**$^{+}$	75.5	72.8	58.1
3DG23	Blue	11.2	8.0	12.3	15.3	7.4	11.9	12.8	10.4	9.1	8.1	6.8	8.9	8.0	8.5	9.4
	Yellow	3.4	6.8	4.2	4.0	5.2	4.0	7.7	7.0	4.7	6.8	7.1	4.0	5.3	10.9	4.2
	Overall	14.6	14.8	16.5	19.3	12.6	15.9	20.5	17.4	13.8	14.9	13.9	12.9	13.3	19.4	13.6
3DG28 (inkjet)	Red	66.8	92.0	59.5	67.4	59.5	77.8	61.7	72.7	74.7	62.5	69.5	67.7	72.4	58.0	74.2
	Cyan	17.7	14.5	20.0	19.2	20.7	15.9	20.5	18.1	16.4	21.1	16.3	15.7	15.7	24.7	14.8
	Overall	**84.6**$^{+}$	**106.5**$^{+}$	79.5	**86.6**$^{+}$	**80.2**$^{+}$	**93.6**$^{+}$	**82.2**$^{+}$	**90.7**$^{+}$	**91.1**$^{+}$	**83.6**$^{+}$	**85.8**$^{+}$	83.3	**88.1**$^{+}$	**82.7**$^{+}$	**89.0**$^{+}$
3DG32	Red	14.1	23.7	9.0	14.7	9.3	17.0	13.1	15.8	15.5	11.7	9.6	7.1	8.7	15.4	12.2
	Cyan	1.0	0.9	1.9	2.2	2.0	1.4	1.2	2.1	1.1	2.6	1.5	1.2	1.8	1.3	0.7
	Overall	15.1	24.6	10.9	17.0	11.3	18.4	14.3	17.9	16.6	14.3	11.1	8.4	10.5	16.7	12.8
3DG51	Blue	18.9	13.0	19.7	23.1	12.1	19.2	20.2	16.5	15.1	13.8	11.7	16.2	13.9	14.8	14.3
	Yellow	3.5	7.1	4.3	4.0	5.2	4.1	8.0	7.2	4.8	6.9	7.3	4.1	5.4	11.1	4.2
	Overall	22.4	20.1	24.0	27.1	17.3	23.3	28.2	23.7	19.9	20.8	18.9	20.3	19.3	25.9	18.5
3DG67	Blue	9.9	7.1	11.2	13.8	6.8	10.5	11.4	9.6	8.1	7.6	6.3	8.2	7.4	8.6	8.2
	Yellow	3.3	6.7	4.1	3.9	5.2	4.0	7.7	6.9	4.6	6.7	7.1	4.0	5.2	10.8	4.1
	Overall	**13.2**$^{\#}$	**13.7**$^{\#}$	15.4	17.7	12.0	**14.4**$^{\#}$	19.1	**16.5**$^{\#}$	**12.7**$^{\#}$	14.3	13.3	12.1	12.7	19.4	12.4
3DG68	Green	5.1	7.7	7.3	7.9	9.3	6.2	12.6	10.6	6.6	10.4	9.8	6.0	8.1	15.6	6.2
	Magenta	11.4	15.3	6.3	12.1	6.5	13.4	8.0	10.1	11.6	6.4	5.5	5.1	5.9	6.6	10.1
	Overall	16.4	23.0	13.6	20.1	15.8	19.6	20.6	20.7	18.2	16.8	15.2	11.2	14.0	22.2	16.3
3DG69	Blue	10.8	7.7	12.1	14.7	7.4	11.3	12.3	10.3	8.8	8.2	6.8	9.0	8.1	9.2	8.9
	Yellow	3.4	6.8	4.2	4.0	5.2	4.0	7.7	7.0	4.7	6.7	7.1	4.0	5.3	10.8	4.2
	Overall	14.2	14.5	16.3	18.7	12.5	15.3	20.0	17.2	13.5	14.9	14.0	13.0	13.4	20.0	13.1
3DG70 (dichroic)	Red	13.4	22.6	8.2	13.9	8.3	16.1	12.3	15.0	14.7	10.9	8.5	6.4	7.9	14.7	10.9
	Cyan	1.0	0.9	2.0	2.2	2.2	1.4	1.3	2.2	1.1	2.9	1.7	1.4	1.9	1.5	0.7
	Overall	14.4	23.5	**10.2**$^{\#}$	**16.1**$^{\#}$	**10.5**$^{\#}$	17.5	**13.6**$^{\#}$	17.1	15.8	**13.8**$^{\#}$	**10.2**$^{\#}$	**7.8**$^{\#}$	**9.8**$^{\#}$	**16.2**$^{\#}$	**11.6**$^{\#}$
3DG71 (dichroic)	Blue	63.9	43.0	64.8	67.6	44.4	63.2	60.7	49.0	50.8	46.0	42.5	64.7	51.5	45.3	49.4
	Yellow	2.4	4.9	3.3	3.0	4.1	3.0	6.8	5.7	3.4	5.2	5.7	3.0	4.1	10.1	2.9
	Overall	66.3	47.8	68.1	70.7	48.5	66.2	67.5	54.7	54.3	51.2	48.2	67.7	55.6	55.4	52.2
3DG72 (dichroic)	Green	5.8	8.8	8.5	9.0	10.5	7.0	14.1	12.0	7.5	12.2	11.2	7.0	9.4	17.6	6.9
	Magenta	9.7	12.1	5.4	10.9	5.6	11.4	7.3	8.5	9.5	5.4	4.9	4.2	4.8	5.7	9.1
	Overall	15.5	20.8	13.9	19.9	16.1	18.4	21.4	20.5	17.0	17.6	16.0	11.2	14.1	23.4	16.0
3DG73	Red	15.2	25.1	10.1	15.8	10.8	18.2	13.9	17.1	16.9	12.9	11.0	8.5	10.3	16.6	13.6
	Cyan	2.0	1.8	3.2	3.3	3.2	2.3	2.6	3.1	2.0	4.0	2.3	2.1	2.6	3.2	1.4
	Overall	17.2	27.0	13.4	19.1	14.0	20.5	16.5	20.3	18.9	16.9	13.3	10.6	12.9	19.8	14.9
3DG74	Red	13.5	22.8	8.4	14.1	8.9	16.2	12.6	15.2	14.8	11.3	9.2	6.7	8.4	14.8	11.6
	Cyan	2.1	1.9	3.3	3.4	3.3	2.3	2.6	3.2	2.1	4.0	2.3	2.1	2.7	3.3	1.4
	Overall	15.5	24.7	11.8	17.5	12.2	18.5	15.2	18.4	16.9	15.3	11.5	8.8	11.0	18.2	13.1
3DG75	Green	6.3	9.6	8.8	9.5	10.9	7.4	14.9	12.4	8.1	12.2	11.3	7.1	9.4	18.3	7.6
	Magenta	11.1	14.7	6.2	11.8	6.6	13.1	7.6	10.0	11.4	6.4	5.5	5.3	6.0	6.6	10.0
	Overall	17.4	24.3	15.0	21.3	17.5	20.5	22.5	22.4	19.5	18.6	16.8	12.4	15.4	24.8	17.6
3DG76	Green	6.2	9.5	8.6	9.4	10.8	7.4	14.8	12.3	8.0	12.0	11.2	7.0	9.3	17.9	7.6
	Magenta	10.8	14.2	5.9	11.5	6.2	12.7	7.4	9.6	11.0	6.2	5.2	4.9	5.7	6.4	9.5
	Overall	17.0	23.7	14.6	20.9	17.0	20.0	22.2	22.0	19.0	18.2	16.5	12.0	15.0	24.3	17.1

Key: Overall Crosstalk Factor: **00.0**$^{+}$ = Highest, **00.0**$^{\#}$ = Lowest, 00.0 = Less than 15.

3.4 Validation

A series of first-order validation tests were performed to check the accuracy of the crosstalk model. A set of test images were viewed on CRT and PDP monitors and subjectively ranked in order of increasing crosstalk by human observers. The results of the subjective ranking were then compared with the crosstalk ranking generated by the Matlab program and this is shown in Tables 5(a-f). The first group of validations (Tables 5 a-d) only compare a single filter color at a time. The second group of validations (Tables 5 e and f) compare the overall crosstalk ranking of the glasses (both left and right eye filters) as a whole.

It can be seen that the single lens subjective rankings agree extremely well with the calculated results (Tables 5 a-d). Most of the differences occur where the crosstalk percentage difference was 0.6 or less, which is a very small difference and would be hard to discern by the naked eye.

The validation of the overall crosstalk factor ranking for each overall pair of anaglyph glasses (combining left and right lenses) (Tables 5 e and f) indicates that we are on the right track but there is room for improvement (of either the algorithm or the validation procedure). The overall crosstalk validation experiment on a CRT monitor (Table 5e) was reasonably successful with only two glasses having large ranking differences (3DG4 and 3DG73). The other ranking differences generally had crosstalk factor ranking differences[†] less than 5 points. The ranking of the color groups of glasses also agrees fairly well except for the placement of 3DG4 and 3DG73. The overall crosstalk validation experiment on PDP15 (Table 5f) was seemingly more jumbled than the CRT ranking, but it is also important to note that most of the calculated crosstalk factors fall within a smaller range for PDP15 (12.4 to 18.5 →6.1 range) than for the CRT case (where the equivalent range is 22.8 to 45.4 → 22.6 range). Our previous studies have found that when the crosstalk numbers are closer together it will be harder to visually distinguish the differences. The largest disagreement of ranking for PDP15 are with 3DG69, 3DG51, and 3DG67 – which are all blue/yellow glasses (this is based on the rank position difference, and also the crosstalk factor ranking difference). All of the other ranking differences for PDP15 have a crosstalk factor ranking difference of less than 2 (e.g. for 3DG73 is 14.9-13.1=1.8).

Tables 5(a-f): Anaglyph crosstalk validation tables. Validation of individual filters on a CRT monitor for (a) red filter, (b) cyan filter, (c) blue filter, and (d) yellow filter. Validation of overall ranking of anaglyph glasses on (e) a CRT monitor, and (f) a plasma display. Lines join matching entries. Key: R/C = Red/Cyan, G/M = Green/Magenta, B/Y = Blue/Yellow.

(a) Red Lens Validation (CRT)

Visual Rank	Computed Rank	Calculated Crosstalk
3DG32	3DG32	18.1
3DG26	3DG26	18.5
3DG13	3DG13	19.2
3DG04	3DG04	26.8
3DG10	3DG10	35.1
3DG28	3DG28	108.5

(b) Cyan Lens Validation (CRT)

Visual Rank	Computed Rank	Calculated Crosstalk
3DG10	3DG26	4.6
3DG26	3DG32	4.7
3DG32	3DG10	4.84
3DG04	3DG13	4.88
3DG13	3DG04	4.91
3DG28	3DG28	16.9

(c) Blue Lens Validation (CRT)

Visual Rank	Computed Rank	Calculated Crosstalk
3DG67	3DG67	27.1
3DG23	3DG69	28.7
3DG69	3DG23	30.3
3DG51	3DG51	40.2
3DG22	3DG22	129.5

(d) Yellow Lens Validation (CRT)

Visual Rank	Computed Rank	Calculated Crosstalk
3DG23	3DG22	4.5
3DG51	3DG67	5.09
3DG69	3DG23	5.10
3DG67	3DG69	5.12
3DG22	3DG51	5.2

(e) Anaglyph Glasses Validation (CRT)

Visual Rank	Computed Rank	Calculated Crosstalk
R/C 3DG32	3DG32 R/C	22.8
R/C 3DG4	3DG74 R/C	24.2
R/C 3DG73	3DG68 G/M	24.9
R/C 3DG74	3DG76 G/M	27.3
G/M 3DG68	3DG75 G/M	29.0
G/M 3DG76	3DG73 R/C	29.7
G/M 3DG75	3DG4 R/C	31.7
B/Y 3DG23	3DG67 B/Y	32.2
B/Y 3DG67	3DG69 B/Y	33.8
B/Y 3DG69	3DG23 B/Y	35.4
B/Y 3DG51	3DG51 B/Y	45.4
B/Y 3DG22	3DG28 R/C	125.4
R/C 3DG28	3DG22 B/Y	134.0

(f) Anaglyph Glasses Validation (PDP15)

Visual Rank	Computed Rank	Calculated Crosstalk
R/C 3DG32	3DG67 B/Y	12.4
R/C 3DG74	3DG32 R/C	12.8
R/C 3DG73	3DG74 R/C	13.1
R/C 3DG4	3DG69 B/Y	13.1
B/Y 3DG23	3DG23 B/Y	13.6
B/Y 3DG67	3DG4 R/C	14.2
B/Y 3DG51	3DG73 R/C	14.9
G/M 3DG68	3DG68 G/M	16.3
G/M 3DG76	3DG76 G/M	17.1
G/M 3DG75	3DG75 G/M	17.6
B/Y 3DG69	3DG51 B/Y	18.5
B/Y 3DG22	3DG22 B/Y	58.1
R/C 3DG28	3DG28 R/C	89.0

It should be noted that the accuracy of these validation experiments are limited due to the limited number of conditions tested (CRT and PDP15) and the limited number of observers (1 or 2). The authors would like to expand the validation experiments (primarily by increasing the number of observers) in order to improve the accuracy of the crosstalk calculation model – particularly the calculation of the overall crosstalk factor. It is important to point out that visually comparing anaglyph glasses of different colors was found to be a very difficult task and is also possibly highly subjective. Some aspects discussed in Section 4.2 may also contribute to the accuracy of the validation.

[†] For the purposes of this discussion the crosstalk factor ranking difference is defined by example as follows: On a CRT the calculated crosstalk factor for 3DG4 is 31.7. When visually ranked on a CRT, 3DG4 has rank position 2, which is the same ranking position as 3DG74 in the computed rank column. The calculated crosstalk factor for 3DG74 is 24.2. Therefore the crosstalk factor ranking difference for 3DG4 on a CRT is 31.7-24.2=7.5.

4. DISCUSSION

4.1 General Observations

Crosstalk in anaglyph images acts to degrade the 3D image quality by making them hard to fuse – the corollary of this is that the image quality of anaglyph 3D images can be maximized by minimizing the amount of crosstalk. The simulations of this study predict that the choice of anaglyph glasses can have a major impact on the amount of crosstalk present, therefore a simple change of anaglyph glasses could significantly reduce the amount of crosstalk present. The simulations also predict that the spectral characteristics of a particular display can also have a significant effect on the amount of crosstalk present – one display can exhibit significantly less ghosting than the same image and glasses on another display. Understandably it will usually be harder for a user to swap to a different display to attempt to reduce crosstalk, than it will be to change glasses.

A number of interesting trends can be seen in the crosstalk simulations results of Tables 3 and 4. The crosstalk algorithm predicts that in most cases the pair of anaglyph glasses with the highest level of crosstalk (from the set of glasses considered in this paper across all of the displays considered in this paper) was the inkjet printed pair of glasses 3DG28 (average crosstalk 93.8, global maximum 125.4) – this was not totally unexpected given their very poor stop-band performance. In other words – don't use inkjet printed anaglyph filters. The algorithm predicts that the pair of anaglyph glasses with the lowest level of crosstalk (from the set of glasses considered in this paper across all of the displays considered in this paper) was the red/cyan dichroic-filter glasses 3DG70 (average crosstalk 13.6, global minimum 7.1). This result is probably attributable to the very low stop-band transmission, very high pass-band transmission, sharpness of the transition between stop-band and pass-band, and also the actual wavelength of the transition point for both eyes. Unfortunately a physical sample of these glasses was not available to conduct visual testing so these results should be considered with some skepticism.

The crosstalk algorithm predicts that the cyan and the yellow filters mostly have very low crosstalk figures (an average of 2.2% for the better four cyan gel-filters across all displays and 5.1% for the better four yellow gel-filters). Unfortunately the predicted crosstalk performance of the red and blue filters does not match the low crosstalk performance of the cyan and yellow filters they are usually matched with (red average 13.5% and blue average 20.1%).

Some further summarized data is available in Table 6 which shows that the algorithm predicts that the four better red/cyan gel-glasses will perform similarly on LCD and plasma displays but better than on CRT, that the four better blue/yellow gel-glasses will perform better on plasma displays than on LCD and CRT, and that the green/magenta gel-glasses will perform better on plasma and LCD than with CRT. The algorithm also predicts that CRT will generally exhibit about double the amount of anaglyph crosstalk compared to LCD or plasma. Across all of the better gel-glasses, plasma had the lowest average crosstalk (average of 17.0, global minimum of 8.4), followed by LCD (average of 22.9, global minimum of 7.6) and then CRT (average of 30.3, global minimum of 22.8).

Table 6: Summarized crosstalk simulation results showing average overall crosstalk factor for various anaglyph glasses across various displays.

	Displays		
Average overall crosstalk factor for:	**LCD**	**PDP**	**CRT**
Better four red/cyan gel-filter glasses	14.7	15.7	27.1
Better four blue/yellow gel-filter glasses	33.9	16.9	36.7
All three green/magenta gel-filter glasses	20.1	18.4	27.1
Dichroic red/cyan filter glasses (simulated only)	11.1	13.9	23.4
Dichroic blue/yellow filter glasses (simulated only)	87.9	58.3	126.4
Dichroic green/magenta filter glasses (simulated only)	17.5	17.4	21.6

Please note the limitations of this study as described in Section 4.2.

Comparing the levels of crosstalk between the various color-primary types of anaglyph glasses (choosing the best four gel-glasses of each type, or best three in the case of green/magenta), the algorithm predicts that for LCDs, red/cyan glasses will have the lowest average overall crosstalk (average 14.7, global minimum 7.6), followed by green/magenta (average 20.1, global minimum 11.7), then by blue/yellow (average 33.9, global minimum 24.7). For plasma displays the difference is less marked, with the algorithm predicting that on average the red/cyan glasses will have the lowest crosstalk (average 15.7, global minimum 8.4), closely followed by blue/yellow (average 16.9, global minimum 12.5),

and closely followed by green/magenta (average 18.4, global minimum 11.2). For CRT, the algorithm predicts that on average red/cyan and green/magenta have the same average lowest crosstalk (red/cyan average 27.1, global minimum 22.8) (green/magenta average 27.1, global minimum 24.9), followed by blue/yellow (average 36.7, global minimum 32.2). Across all of the tested displays, the algorithm predicts that red/cyan has the lowest average crosstalk (average 15.7), followed closely by green/magenta (average 19.5), and then blue/yellow (average 25.2).

It was mentioned above that the red/cyan dichroic filter glasses were predicted to have the lowest average crosstalk across all of the tested displays. Let's look more closely at the performance of the other dichroic filters. According to the simulation, the green/magenta dichroic filter glasses have slightly lower crosstalk levels (average 17.6) than the green/magenta gel-filter glasses (average 19.5). This would be for the same reasons cited for the good performance of the red/cyan dichroic filter glasses. On the other hand, the blue/yellow dichroic filter glasses are predicted to have grossly higher average crosstalk levels (average 73.9) than the better blue-yellow gel-filter glasses (average 25.2). Looking more closely at this result, the yellow dichroic filter is predicted to have slightly lower crosstalk than the better yellow gel-filters, but the algorithm predicts the blue dichroic filter to have almost three times the crosstalk as the better blue gel-filters. This will be the source of the high result overall dichroic crosstalk result. Looking at the spectrum of the blue dichroic filter shows that the transition wavelength is around 505nm which is probably too high. If the transition wavelength was closer to 480 or 490nm, the result would probably be very different. The simulation results indicate that dichroic filters have potential to offer lower crosstalk than equivalent gel-filters, providing the transition wavelengths are positioned optimally. It would be interesting to validate these predictions with visual tests on physical pairs of these glasses.

4.2 Limitations of this Study

The techniques used in this study have several limitations which should be considered when the results of this study are reviewed. The study only considers a limited number of displays – it is unclear whether these displays are a valid representation of all displays in common circulation. Furthermore recent model displays may have a different spectral emission performance – for example, LED backlit LCD TVs are likely to have different spectral characteristics and therefore very different crosstalk results.

The crosstalk calculation algorithm only considers crosstalk as an indicator for 3D image quality – there are a number of other factors which also contribute towards the perception of 3D image quality but are not included in the algorithm. For example: clarity or sharpness of the lenses (filters with a low MTF would reduce 3D image quality); brightness balance of the left and right lenses (high brightness imbalance can lead to the perception of the Pulfrich effect – our calculations indicate that the green/magenta glasses generally have better brightness balance and blue/yellow glasses have the greatest brightness imbalance although that work isn't reported here due to space limitations); color balance of the monitor (our tests have revealed that color balance does have an effect on crosstalk calculations but we have not been able to design this out of the algorithm at the present time); experimental variation and product manufacturing variation; the inherent difficulty of accurately visually comparing relative brightness of different colors; and other psychological effects (which can lead to subjective variation).

The current crosstalk simulation algorithm uses a simple addition of left eye crosstalk and right eye crosstalk to obtain the overall crosstalk factor for a pair of glasses. This may not be a good representation of how we perceive overall levels of crosstalk – particularly when there are large brightness differences and large crosstalk differences between the eyes. One example of this is glasses 3DG51 on a CRT – the crosstalk of the blue filter has almost eight times the amount of crosstalk of the yellow lens (which has quite low crosstalk). The yellow lens is also substantially brighter than the blue lens. When glasses 3DG51 are worn, the perception of the brighter yellow lens seems to dominate the perception of the 3D image and less crosstalk is perceived than a simple addition of yellow and blue individual crosstalk would suggest. Further work is required in this area and would be aided by an expanded validation experiment as mentioned in Section 3.4.

This study also ignores the introduction of anaglyph crosstalk by the use of lossy compression techniques on anaglyph images (e.g. JPEG compression), and the use of incorrect anaglyph generation algorithms (which may unwittingly mix left and right images). These effects are quite separate from the spectral techniques described in this paper and should be considered separately. Anaglyph content producers should work to ensure that their anaglyph 3D content is not adversely affected by these last two factors.

5. CONCLUSION

Although there are a range of other stereoscopic display technologies available that produce much better 3D image quality than the anaglyph 3D method (e.g. polarized, shutter glasses, and Infitec), the anaglyph 3d method remains widely used because of its simplicity, low cost, and compatibility with all full-color displays and prints. If anaglyph 3D is to be used, it would be best if it were used optimally which is one of the purposes of this paper.

This paper has revealed that crosstalk in anaglyphic 3-D images can be minimized by the appropriate choice of anaglyphic 3-D glasses. The study has also revealed that there is considerable variation in the amount of anaglyphic crosstalk exhibited by different displays. Compared to previous work that has only considered red/cyan anaglyph glasses, this paper has extended the work to include blue/yellow and green/magenta anaglyph glasses which are now also in common usage. The paper has also considered the effect of using dichroic filters and inkjet printed filters for anaglyph 3D viewing. The techniques used in the paper to simulate anaglyph crosstalk are by no means perfect at this stage, but they do confirm that there is considerable opportunity for the optimization of anaglyph viewing by the appropriate choice of anaglyph glasses and displays.

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