Andrew J. Woods, Tegan Rourke, "Ghosting in Anaglyphic Stereoscopic Images", presented at Stereoscopic Displays and Applications XV, published in Stereoscopic Displays and Virtual Reality Systems XI, Andrew J. Woods, Mark T. Bolas, John O. Merritt, Stephen A. Benton, Editors, Proceedings of SPIE-IS&T Electronic Imaging, SPIE Vol. 5291, San Jose, California (2004)

Ghosting in Anaglyphic Stereoscopic Images

Andrew J. Woods*, Tegan Rourke
Centre for Marine Science & Technology (CMST), Curtin University of Technology

ABSTRACT

Anaglyphic 3D images are an easy way of displaying stereoscopic 3D images on a wide range of display types, eg. CRT, LCD, print, etc. While the anaglyphic 3D image method is cheap and accessible, its use requires a compromise in stereoscopic image quality. A common problem with anaglyphic 3D images is ghosting. Ghosting (or crosstalk) is the leaking of an image to one eye, when it is intended exclusively for the other eye. Ghosting degrades the ability of the observer to fuse the stereoscopic image and hence the quality of the 3D image is reduced. Ghosting is present in various levels with most stereoscopic displays, however it is often particularly evident with anaglyphic 3D images. This paper describes a project whose aim was to characterise the presence of ghosting in anaglyphic 3D images due to spectral issues. The spectral response curves of several different display types and several different brands of anaglyph glasses were measured using a spectroradiometer or spectrophotometer. A mathematical model was then developed to predict the amount of crosstalk in anaglyphic 3D images when different combinations of displays and glasses are used, and therefore predict the best type of anaglyph glasses for use with a particular display type.

Keywords: Anaglyph, stereoscopic, 3D, crosstalk, ghosting, image quality.

1. INTRODUCTION

There are many methods of displaying a stereoscopic image, including polarized images, time-sequential alternating frames, two separate images viewed through a binocular lens arrangement, and others. The method used in this project is the anaglyph. Here, the two perspective images are combined into a single image using a complimentary colour coding technique. For example, if a red/cyan anaglyph method is used, the left perspective image is stored in the red channel and the right perspective image is stored in the blue and green colour channels (blue + green = cyan). The observer wears a pair of glasses with one eye's filter coloured red, and the other eye's filter coloured cyan. The filters act to permit the transmission of the correct image to each eye but prevent the transmission of the image not intended for that eye. The brain processes the different perspective images and depth is perceived in the image.

Anaglyphic 3D encoding can be performed using any pair of complimentary colours to store the left and right perspective images. Red/cyan is the most common choice however yellow/blue is also used, and green/magenta is also theoretically possible. The combination of red/blue or red/green can also be used – however brightness is reduced because one of the colour channels is missing in each case.

The main advantages of the anaglyphic 3D method are its simplicity and low cost. All that is required is an anaglyphic 3D image, which can be displayed using almost any colour display method, and a corresponding pair of anaglyphic 3D glasses.

The main disadvantages of anaglyphic images are their inability to accurately depict full-colour images, and the presence of crosstalk. Crosstalk or ghosting is the leaking of an image to one eye, when it is intended exclusively for the other eye. It happens with most stereoscopic displays and results in reduced image quality and difficulty of fusion if the crosstalk is large. Possible sources of crosstalk in anaglyphic images are:

- **Display spectral response**
  Most emissive type displays (e.g. CRTs, LCDs, DMDs) work by emitting light in three specific primary colour bands (red, green and blue). The actual spectral content of each light band can vary quite considerably between different display types. If the spectrum of the primary colour bands overlap with each other by any significant

* A.Woods@cmst.curtin.edu.au; phone: +61 8 9266 7920; fax: +61 8 9266 4799; http://www.cmst.curtin.edu.au; Centre for Marine Science & Technology, Curtin University of Technology, GPO Box U1987, Perth 6845, AUSTRALIA.

amount, it will be difficult to separate those two colours by the use of colour filters. Ideally the spectral output of each primary colour channel would not overlap.

- **Anaglyph glasses spectral response**
  Ideally the filters in anaglyph glasses will only pass light in the selected light bands – e.g. red 600-650nm. If the anaglyph filters still passes light in the undesirable domain, a dim, ghosted image may be seen if the display is still active in those wavelengths.
- **Image compression**
  Some image compression formats (e.g. JPEG, MPEG, GIF) can mix information between the three RGB colour channels and hence also introduce crosstalk into anaglyphic 3D images. The amount of crosstalk introduced will depend on the amount of compression used, the type of compression used, and sometimes the particular encoding method used for a particular compression type.
- **Image encoding and transmission**
  The two main analogue consumer video formats (NTSC and PAL) encode the colour information as two colour difference signals (at a lower bandwidth than the brightness (luminance) information) multiplexed on top of the luminance signal using a process of Quadrature Amplitude Modulation. Unfortunately this technique also results in the mixing of information between the three RGB colour channels and hence also causes crosstalk

This paper considers the first two points (display spectral response and anaglyphic glasses spectral response).

The reason for this paper is that anaglyphs can often exhibit a lot of ghosting, but the amount of ghosting depends greatly on the type of glasses used and the type of display used. Although ghosting in time-sequential stereoscopic images has been studied[1,2,3], relatively few papers have been published on the topic of image quality in anaglyphic 3D images[4]. Our goal was therefore to understand the process of ghosting and hopefully reveal options for reducing ghosting in anaglyphic 3D images.

This paper only examines crosstalk in red/cyan anaglyphic 3D images, although the method discussed could also be applied to the less common blue/yellow anaglyphs or rare green/magenta anaglyphs. Some of the tested glasses were intended for printed anaglyphs, but this paper only considers emissive type displays; other glasses may be better for viewing printed anaglyphs.

2. EXPERIMENTAL METHOD

Figure 1 provides an illustration of the experimental method used in this project. The first step was to characterise the spectral response of the anaglyph display (eg CRT, LCD, or projector). The second step was to characterise the spectral response of the anaglyphic 3D glasses. The third step was to write a computer program to analyse the data from the previous two steps. The computer program (written in Maple 7) calculated a ghosting integral and uncertainties. The fourth step was to generate output from the program that was representative of the crosstalk in the image.

2.1 Measurement of display spectral output

The spectral output of several CRT monitors and a laptop computer LCD were obtained from a previous study[1,2]. The spectral response of several digital projectors was measured using the irradiance input of a Zeiss Spectroradiometer assembly consisting of an optical fibre bundle inputting to a Zeiss Monolithic Miniature-Spectrometer (MMS) with a sensitive range from UV to just beyond visible (190 to 735 nm). The projectors were connected to a laptop, which displayed a “PowerPoint” slide show, consisting of a plain white slide (R=G=B=255), a plain black slide (R=G=B=0), a plain red slide (R=255, G=B=0), a plain green slide (R=B=0, G=255) and a plain blue slide (R=G=0, B=255).

2.2 Measurement of spectral tranmission of filters

A Hitachi model 150-20 spectrophotometer (SPM) was used to measure the transmission spectrum (restricted to 350–750 nm) of each of the two filters (eg red and cyan) in each of 27 pairs of anaglyph glasses. The SPM compared light sent through the glasses’ filter to a reference beam at each wavelength to determine the percentage transmitted. The resulting printed graphs were scanned and then digitised using Windig 2.5, a program written by Dominique Lovy[5].

2.3 Data analysis and crosstalk calculation

A computer program was written in Maple to calculate an estimate of the amount of ghosting present when viewing an anaglyphic 3D image displayed on a particular display whilst wearing a particular pair of anaglyphic 3D glasses.

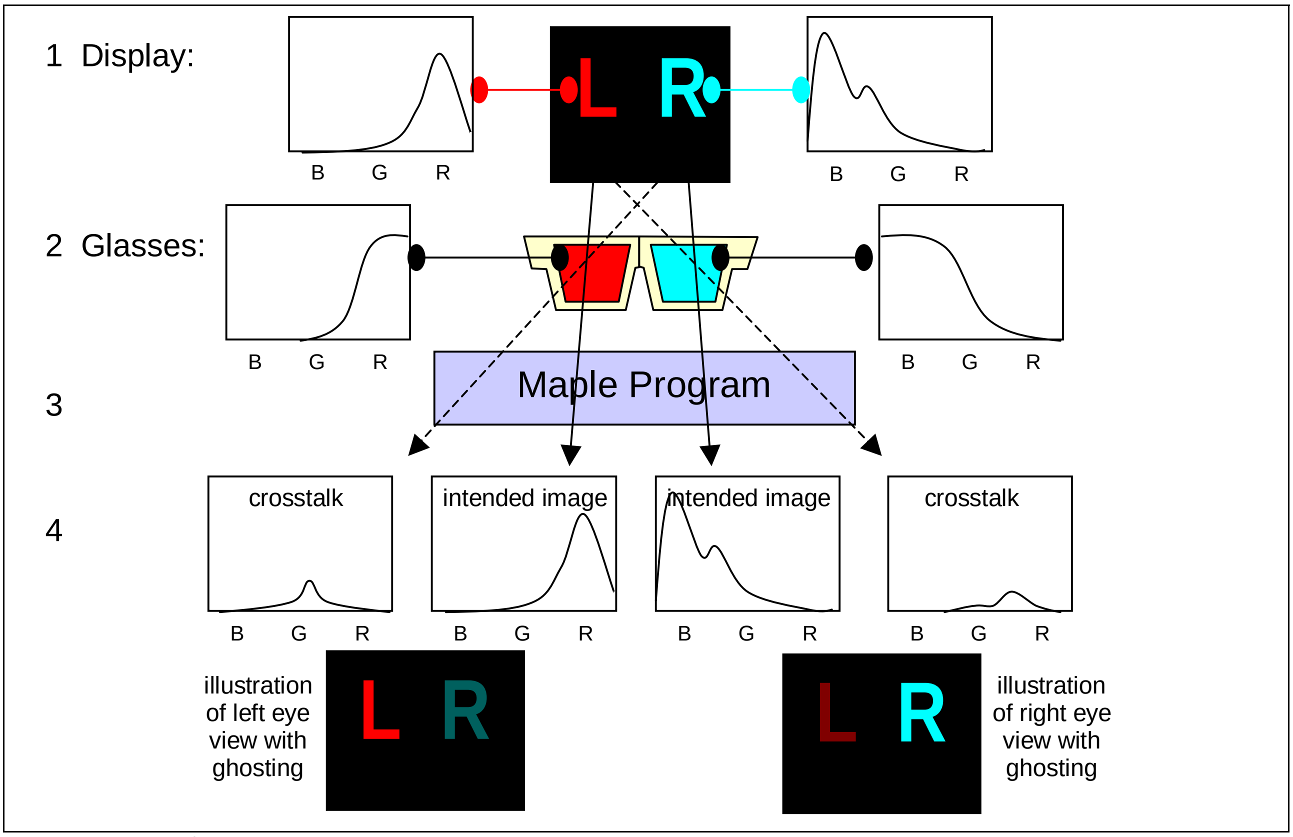


Figure 1: Subset of project plan. Step 1: Characterise display spectral response; Step 2: Characterise glasses spectral response; Step 3: Analyse the data using a computer program; Step 4: Generate estimated output characteristic of crosstalk.

With reference to Figure 1, the program first loads and resamples the display and filter spectral data so that all data is on a common x-axis co-ordinate system. Next, the program determines the display's cyan spectral output by adding the green and blue channel data of the display. The program then multiplies the red display spectrum with the red filter's spectral response to obtain the intended image curve for the red eye, multiplies the cyan display spectrum with the cyan filter's spectrum to obtain the intended image curve for the cyan eye, multiplies the red display spectrum with the cyan filter's spectral response to obtain the crosstalk curve for the cyan eye, and multiplies the cyan display spectrum with the red filter's spectrum to obtain the intended image curve for the red eye.

The program also scales the results to include the human eye's response to light. The human eye has two light detection cell types, rods and cones. Cones, which contain three chemicals that are light-selective pigments, sense colour information. Cones are less sensitive to low light intensities, so are only active in bright or daylight (photopic) vision[6,7]. Cones are not equally sensitive to all colours. The CIE (Commission Internationale de l'Éclairage or International Commission on Illumination) has published a model that is the standard for simulating photopic (bright light) human eye response, normalised about the peak of 555 nm (see Figure 2)[8]. This standard is the result of physical and psychological experiments relating the output of the human colour vision system with measurements of wavelength and intensity[9]. Figure 2 shows how the cones are more sensitive to yellowish light. This has implications for the ghosting model. If a ghosting level of 2% of image output occurs in the blue light region, this will not be very obvious since the eye is not very sensitive to the light in the blue region.

Figure 3 illustrates the Maple program's analysis of real data. Firstly, (a) display device data and filter data are read into the program. (b) At each wavelength and each display colour, the display intensity, filter response and eye's response are multiplied together. (c) The program calculates the total area under each perceived intensity graph. (d) To find the % crosstalk for a filter, the area under the ghost signal curve is divided by the area under intended signal curve and multiplied by 100.

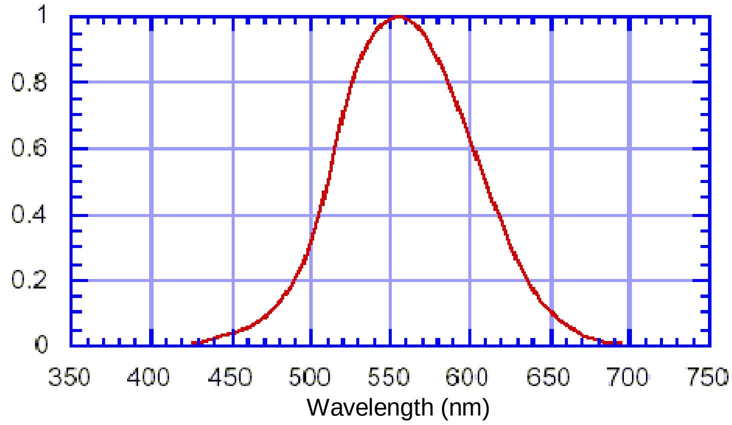
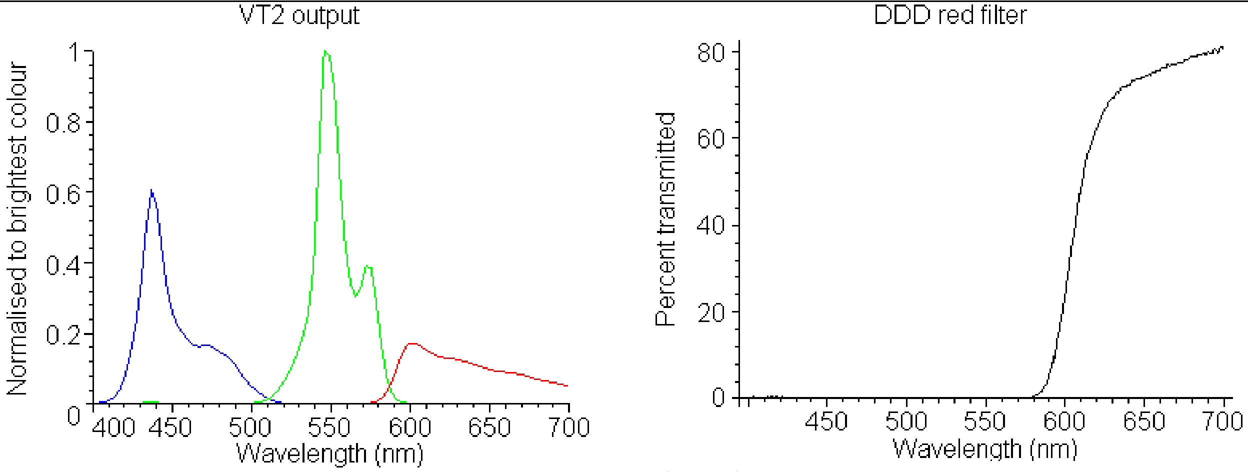
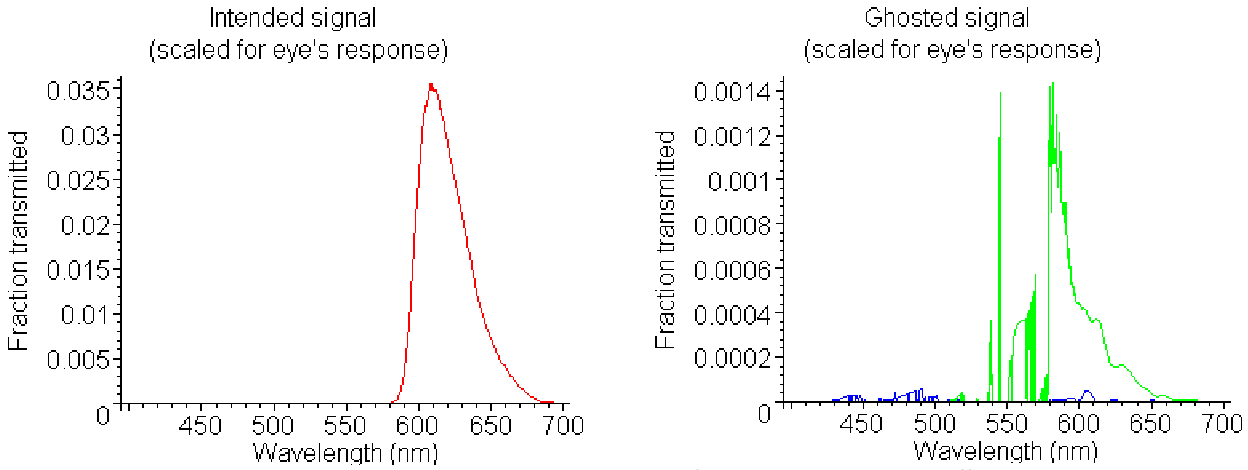


Figure 2: The CIE standard normalised photopic (bright light) human eye response. Figure after Ohno (1999).



(a) Read in display device data (left) and filter data (right).



(b) Calculated intended signal and ghost image intensity (scaled for eye's response). (note different vertical scale)

(c) Area under red curve: 1.411 units

Area under green curve: 0.0372 units;
Area under blue curve: 0.0017 units
Area under cyan curve: 0.0389 units

(d) % Crosstalk = 0.389 ÷ 1.411 × 100 = 2.75%

Figure 3: A step-by-step case of the Maple program's analysis of real data.

The overall crosstalk factor for a particular pair of glasses is the sum of the two filter % crosstalk values. It is not a percentage, but rather a number that allows the comparison of any glasses analysed by the Maple program. The program also automates the process of performing a cross comparison of all the displays against all of the glasses.

3. RESULTS

3.1 Display device results

The spectral response of 11 CRT screens and also an LCD were obtained in a previous study[1,2]. Seven more digital projector spectral outputs were characterised. The details of the displays are summarised in Table 1. As minimal difference was found between the spectral responses of CRTs[1,2], only one typical CRT is listed.

Table 1: Summary of the displays whose spectral outputs were characterised.

Display Type	**Technology**[α]	**Brand**	**Model**	**Abbreviated Name (used in this paper)**
CRT Screen[1,2]	P22 RGB Phosphors	Mitsubishi	Diamond View 1772ie	Diamond CRT
LCD Screen[1,2]	Liquid Crystal	Acer	Laptop Light	Acer LCD
Digital Projector	1 chip DLP	NEC	MultiSync LT81/G	NEC3
Digital Projector	1 chip DLP	Infocus	LitePro 620	Infocus
Digital Projector	3× LCD TFT Panels	Epson	EMP-5500	Epson
Digital Projector	3× LCD p-Si TFT	NEC	VT540/K	VT2
Digital Projector	3× LCD p-Si TFT	NEC	VT540/K	VT6
Digital Projector	3× LCD TFT Panels	Boxlight	3600	Boxlight 2
Digital Projector	3× LCD TFT Panels	Boxlight	3600	Boxlight 3

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

Figure 4 shows the spectral output of the various displays measured in this study. The left column of plots shows the spectral response of all displays for a specific colour primary, eg all displays when showing a red screen. The right column of plots shows the spectral response for all three colour primaries for three specific displays (CRT, laptop LCD, and LCD projector). With reference to Figure 4, it can be seen that the CRT green and blue phosphors outputs are active over a large bell shaped region of the visible spectrum, and overlap the part of the region in which the red phosphor is active. The LCD screen red, blue and green spectra are active throughout the whole visible spectrum, with just an increase in intensity at the wavelengths associated with their colours. Most of the digital projectors have similar shaped curves, though intensity (relative to the brightest colour) varies between projectors.

[α] LCD = Liquid Crystal Display; TFT = Thin Film Transistor; DLP= Digital Light Processor (same as Digital Micromirror Device DMD).[10]

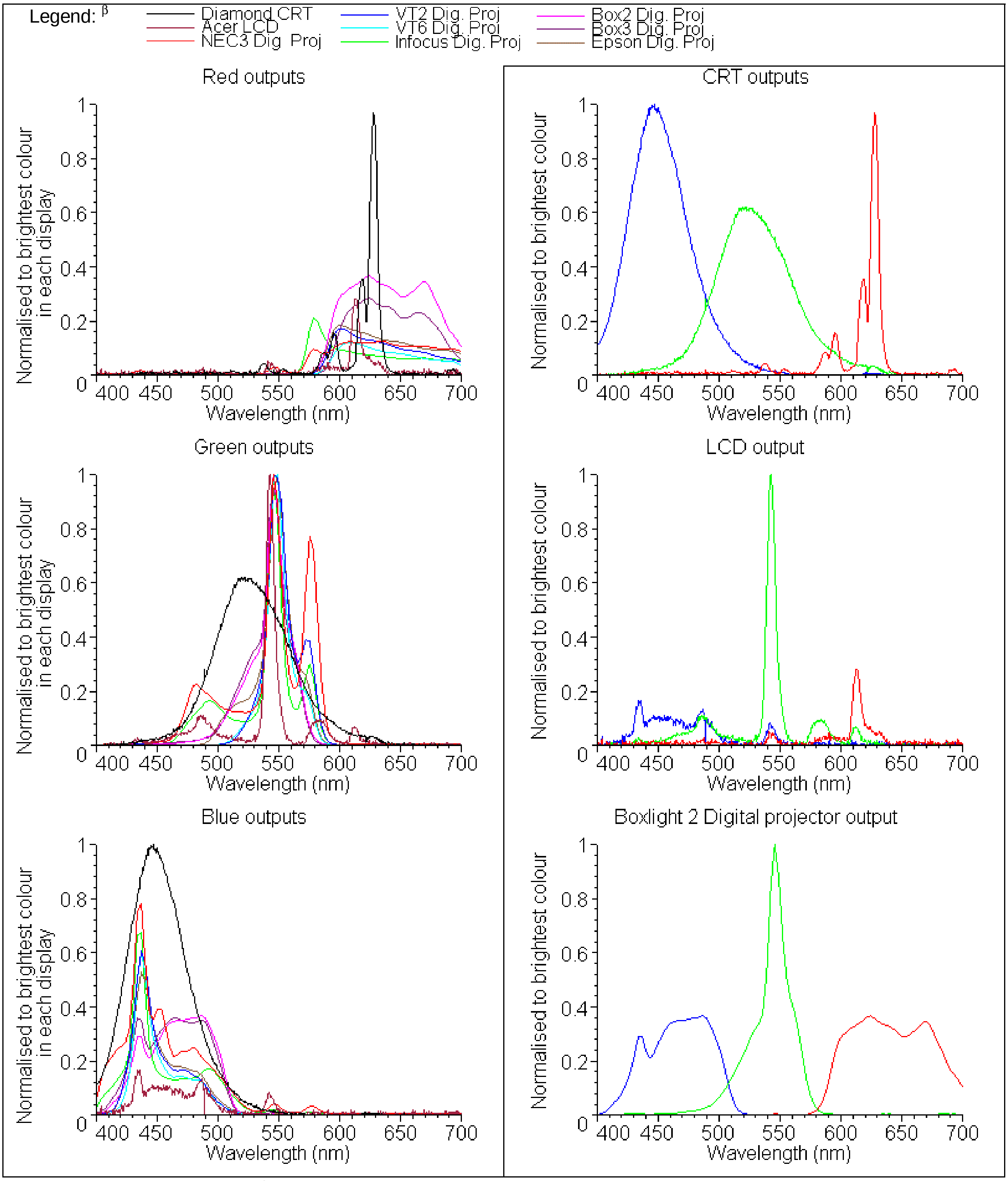


Figure 4: The spectral responses of the various displays tested.

β We realise the legend of some of the figures in this paper won't be distinguishable when printed in black and white. A colour version of the graphs is available from the primary author's website.

3.2 Anaglyph filter results

To fulfil Step 2 of the plan, data characterising the transmission spectra of various anaglyphic 3D glasses were acquired. Table 2 lists the various red/cyan anaglyphic 3D glasses measured.

Table 2: Red/Cyan Anaglyphic glasses measured.

Glasses Number	**Name**	**Other information on glasses**
3DG 2	IMAX/OMNIMAX	"Fujitsu presentation of “We are born of stars”; © IMAX Systems Corp., 1986; Made in USA by Theatric Support, Studio City, California."
3DG 3	National Geographic	Distributed with August 1998 edition of National Geographic Magazine
3DG 4	Sports Illustrated	Distributed with Winter 2000 edition of Sports Illustrated magazine (US edition). "MFGD by Theatric Support."
3DG 6	3D Greets	Attached to a pseudo-colour anaglyph postcard of a Tiger.
3DG 8	Spectacles	"Theatric Support, Studio City CA" Hard-rimmed spectacles purchased from Reel-3D.
3DG 9	Bugs!	From *Bugs!* magazine series
3DG 11	[no name]	[no identification or writing on glasses – white cardboard]
3DG 14	Reel 3D #1	Purchased from Reel-3D – apparently made by Theatric Support.
3DG 15	Reel 3D #2	Purchased from Reel-3D.
3DG 16	Freddy's Dead	"*The Final Nightmare*; New Line Cinema 1991" Distributed at showings of the movie "Freddy's Dead: The Final Nightmare"
3DG 17	3D Video Glasses	"© 1982 3D Video Corp., N. Hollywood, California; for use with 3D Video electronically processed TV programs"
3DG 18	Rhino Home Video	“*Cat Women of the Moon*”, “*Robot Monster*” & “*The Mask*”
3DG 19	DDD	“www.ddd3d.com Dynamic Digital Depth”. Supplied by American Paper Optics.
3DG 20	ABC	"96/97 new season premiere; http://abc.com"
3DG 21	Optic Boom	“A DDD Product; ddd.com"
3DG 24	Studio 3D	"Stereoscopic imaging; www.studio3d.com"
3DG 25	Sports Illustrated Australian Edition	Distributed with March 2000 edition of Sports Illustrated magazine (Australian edition).
3DG 26	Substance Comic	Distributed with “3-D Substance #2" Comic, by Jack C. Harris and Steve Ditko and The 3-D Zone. ©1991.
3DG 27	Deep Vision 3D of Hollywood	"For Deep Vision 3-D TV"
3DG 28	Canon ink	Canon Ink (BCI-3e C/M/Y) printed on inkjet transparency sheet
3DG 29	Spy Kids 3D	"© 2003 Miramax Film Corp.; www.spykids.com, Troublemaker Studios, Dimension Films; Mfrd by Playwerks Inc., USA "

PLEASE NOTE: Although a wide selection of glasses was studied, 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.

Figure 5 shows the combined spectral responses of the filters from the glasses listed in Table 2, grouped according to colour. It is interesting to note that there appears to be a cluster of red and cyan filters in Figure 5 that all trend along the same path. One distinct cyan cluster consists of the cyan filters of the following glasses: 3DG 6, 3DG 15, 3DG 16, 3DG 17, 3DG 19 and 3DG 21. A second distinct cyan cluster consists of the cyan filters of the following glasses: 3DG 3, 3DG 11 and 3DG 20. There are also two distinct red clusters. The first consists of the red filters of the glasses: 3DG 15, 3DG 19 and 3DG 21, and the second consists of the red filters of the glasses: 3DG 4, 3DG 9, 3DG 14 and 3DG 24. It is possible that the same chemicals are used to produce these clustered filters. Three pairs of glasses cluster together in both the red and cyan filters: 3DG 15, 3DG 19 and 3DG 21. These are probably manufactured by the same company and distributed to other companies. The fact that this path presents as a path, and not a single line, could indicate either production variability or be an artefact of the experimental procedure.

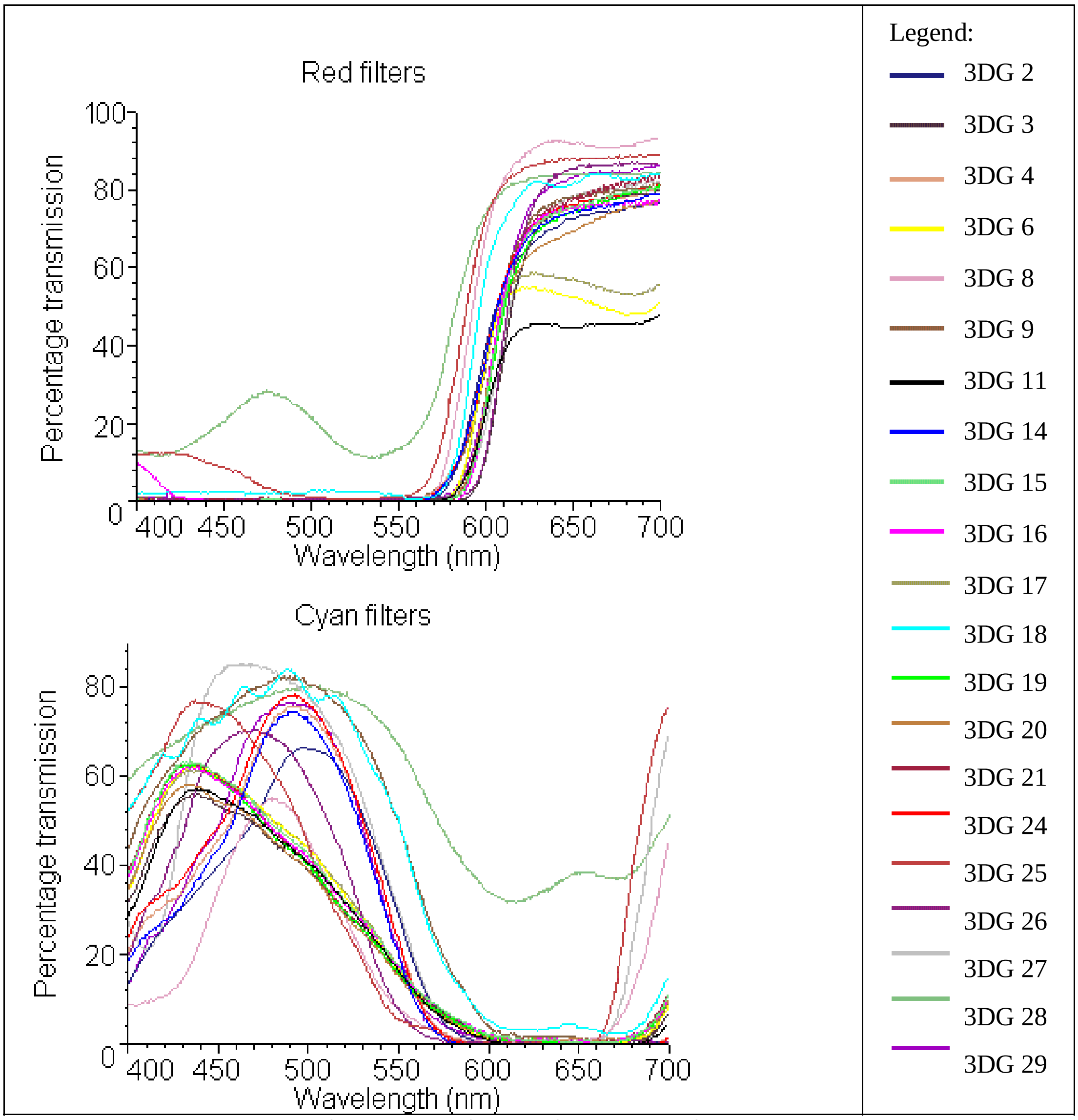


Figure 5: The spectral responses of the anaglyph filters (2 filters per set of glasses).

Figure 6 shows the individual spectral response for three selected pairs of glasses as an example of the variation between pairs of glasses. The red filter of glasses 3DG19 remains at close to 0% transmission from 400 to 570nm (encompassing the green and blue regions) whereas the red filter of glasses 3DG25 has significant leakage in this region (only being close to 0% transmission between 500 and 550 nm). The cyan filter of 3DG25 has a maximum transmission of ~80% in its required pass region, but its transmission also increases rapidly in the >650 nm region. The cyan filter of 3DG19 has a maximum transmission of ~60%, so it will appear dimmer than the cyan filter of 3DG25. The red and cyan filters of 3DG28 are particularly poor but this is understandable due to the use of printing ink.

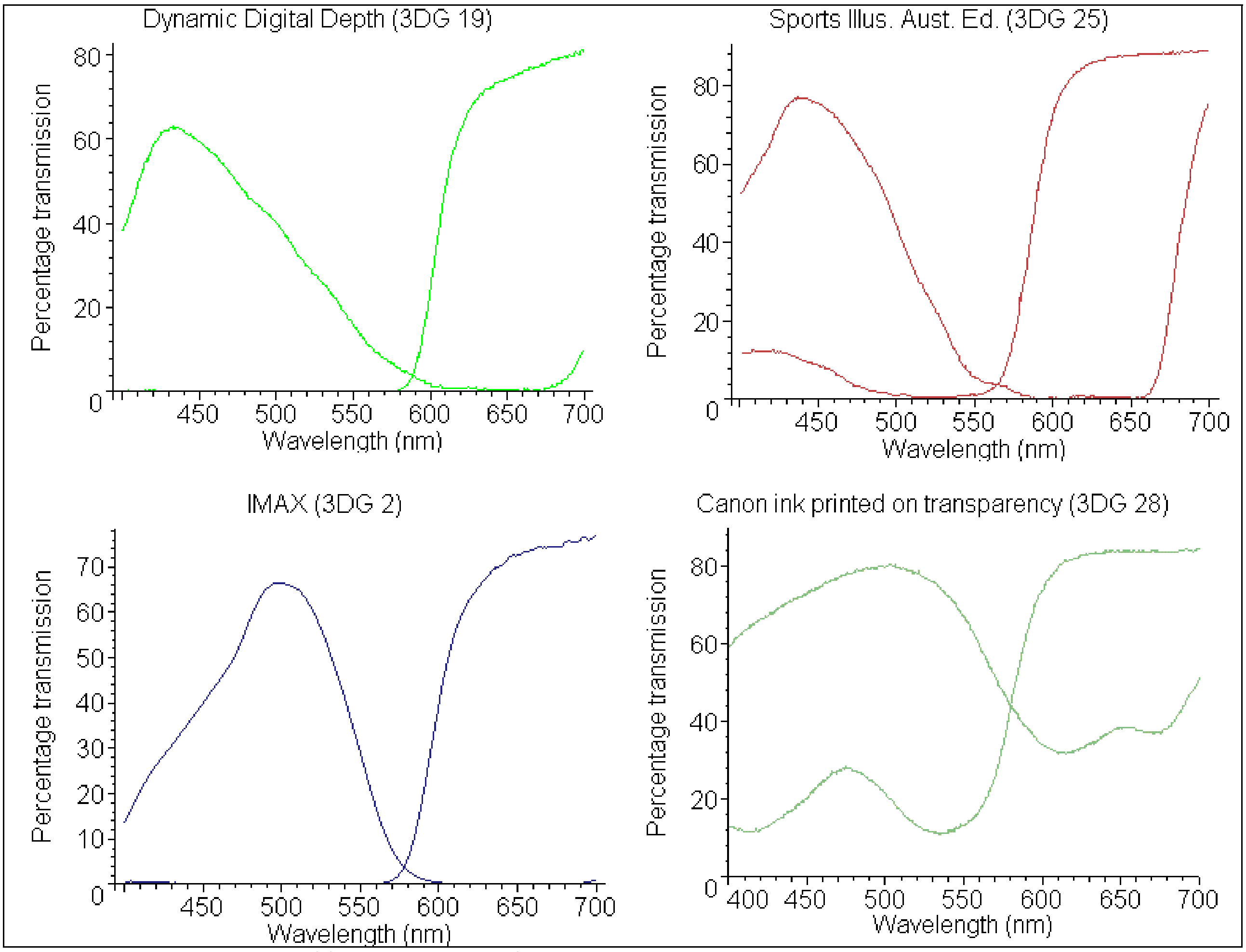


Figure 6: The spectral response of four selected pairs of anaglyph glasses.

3.3 Crosstalk calculation results

The crosstalk results (and uncertainty) calculated by the Maple program for the combination of displays and glasses listed are shown in Table 3. Uncertainties are estimated as 1σ mean error. Note that while the % crosstalk for a filter is a percentage, the overall crosstalk *factor* for a pair of glasses (being the sum of the two filter % crosstalk values) is not a percentage, just a number that allows the comparison of any glasses analysed by the program.

The Maple program also generates a separate table listing the % crosstalk for each individual filter. This allows the user to select the best filters from different glasses and combine them in order to obtain the lowest crosstalk available for that particular display from all available filters. Table 4 summarises this output into lists of the best glasses, best individual filters and corresponding crosstalk factor or percent for each display.

Table 3: Calculated Overall Crosstalk Factor (and uncertainty) for various anaglyph glasses in combination with various RGB display device when viewing ***red/cyan*** anaglyph 3D images. The lowest crosstalk combinations are highlighted in grey – the worst crosstalk results are highlighted in black. The table is sorted on overall crosstalk factor for CRT displays. Uncertainties are estimated as 1σ mean error.

Glasses Number	Diamond CRT	Acer LCD Display	NEC3 1DMD Proj	Infocus 1DMD Proj	Epson 3LCD Proj	VT2 3LCD Proj	VT6 3LCD Proj	Boxlight2 3LCD Proj	Boxlight3 3LCD Proj
3DG 19	22.5 ± 0.3	41.6 ± 0.6	20.9 ± 0.3	8.9 ± 0.2	3.92 ± 0.08	4.66 ± 0.09	3.93 ± 0.08	4.21 ± 0.07	5.19 ± 0.09
3DG 16	23.1 ± 0.3	41.2 ± 0.6	20.1 ± 0.3	9.5 ± 0.2	4.58 ± 0.09	5.0 ± 0.1	4.7 ± 0.1	4.72 ± 0.08	5.8 ± 0.1
3DG 15	23.4 ± 0.3	43.0 ± 0.6	22.9 ± 0.3	11.0 ± 0.2	5.2 ± 0.1	6.3 ± 0.1	5.7 ± 0.1	4.85 ± 0.08	5.9 ± 0.1
3DG 21	24.8 ± 0.4	43.2 ± 0.6	22.9 ± 0.3	10.8 ± 0.2	5.15 ± 0.09	5.9 ± 0.1	5.5 ± 0.1	4.97 ± 0.08	6.3 ± 0.1
3DG 20	25.7 ± 0.4	45.7 ± 0.7	26.2 ± 0.4	13.7 ± 0.2	7.1 ± 0.1	8.6 ± 0.1	8.4 ± 0.2	5.57 ± 0.09	7.1 ± 0.1
3DG 11	27.0 ± 0.4	45.2 ± 0.7	28.0 ± 0.4	11.1 ± 0.2	4.03 ± 0.09	6.1 ± 0.1	4.4 ± 0.1	3.14 ± 0.06	4.59 ± 0.09
3DG 29	27.1 ± 0.4	47.2 ± 0.7	31.9 ± 0.4	14.9 ± 0.2	7.6 ± 0.1	10.3 ± 0.2	9.3 ± 0.1	4.81 ± 0.07	7.1 ± 0.1
3DG 27	27.5 ± 0.4	48.8 ± 0.7	33.4 ± 0.5	17.2 ± 0.3	9.0 ± 0.1	11.7 ± 0.2	11.2 ± 0.2	5.40 ± 0.08	8.1 ± 0.1
3DG 26	29.0 ± 0.4	49.7 ± 0.7	38.3 ± 0.6	26.0 ± 0.4	17.3 ± 0.3	20.7 ± 0.3	21.3 ± 0.3	9.4 ± 0.1	13.1 ± 0.2
3DG 03	29.7 ± 0.4	52.4 ± 0.7	37.2 ± 0.6	31.5 ± 0.5	19.3 ± 0.3	21.2 ± 0.3	23.5 ± 0.4	11.0 ± 0.2	14.5 ± 0.2
3DG 06	30.4 ± 0.4	48.8 ± 0.7	30.5 ± 0.4	12.6 ± 0.2	5.1 ± 0.1	7.5 ± 0.1	5.9 ± 0.1	4.04 ± 0.07	5.7 ± 0.1
3DG 14	31.3 ± 0.5	52.2 ± 0.7	49.9 ± 0.7	17.8 ± 0.3	7.5 ± 0.1	14.9 ± 0.2	9.6 ± 0.2	3.08 ± 0.06	5.25 ± 0.09
3DG 24	31.3 ± 0.5	52.2 ± 0.7	50.9 ± 0.7	18.2 ± 0.3	7.6 ± 0.1	15.0 ± 0.2	9.7 ± 0.2	3.15 ± 0.06	5.29 ± 0.09
3DG 09	36.2 ± 0.5	55.4 ± 0.8	54.7 ± 0.8	26.6 ± 0.4	13.5 ± 0.2	20.6 ± 0.3	16.1 ± 0.2	7.2 ± 0.1	9.3 ± 0.1
3DG 17	36.7 ± 0.5	53.6 ± 0.8	33.2 ± 0.5	17.0 ± 0.3	8.5 ± 0.1	10.7 ± 0.2	10.2 ± 0.2	6.13 ± 0.09	8.4 ± 0.1
3DG 08	39.1 ± 0.5	62.3 ± 0.9	73 ± 1	25.8 ± 0.4	11.2 ± 0.2	23.1 ± 0.3	14.5 ± 0.2	4.92 ± 0.08	7.0 ± 0.1
3DG 04	39.7 ± 0.6	57.7 ± 0.8	55.7 ± 0.8	24.2 ± 0.3	12.5 ± 0.2	20.0 ± 0.3	15.8 ± 0.2	5.87 ± 0.09	9.0 ± 0.1
3DG 02	42.5 ± 0.6	61.2 ± 0.8	53.1 ± 0.7	20.1 ± 0.3	9.0 ± 0.1	15.8 ± 0.2	11.8 ± 0.2	4.42 ± 0.07	7.0 ± 0.1
3DG 18	58.6 ± 0.8	75 ± 1	73.5 ± 1.0	45.5 ± 0.6	26.1 ± 0.4	31.8 ± 0.4	33.0 ± 0.5	16.8 ± 0.2	23.4 ± 0.3
3DG 25	62.7 ± 0.9	82 ± 1	92 ± 1	48.5 ± 0.7	31.5 ± 0.4	51.9 ± 0.7	42.6 ± 0.6	14.3 ± 0.2	20.2 ± 0.3
3DG 28	217± 2	197 ± 2	275 ± 3	169 ± 2	155 ± 2	190 ± 2	205 ± 2	92.9 ± 0.9	125 ± 1

Table 4: Optimal combinations of the measured displays and 3D glasses for a red/cyan image. When a blue or green filter has the lowest crosstalk, the lowest cyan filter is also given.

Display	Best glasses	Overall Crosstalk factor	Best red filter	% Crosstalk	Best cyan filter	% Crosstalk
Diamond CRT	"DDD"	22.5±0.3	DDD red	19.5±0.3	Reel 3D #1 cyan	2.20±0.03
Acer LCD	"Freddy's…"	41.2±0.6	Freddy's. red	34.3±0.5	IMAX cyan	5.63±0.08
NEC3 1DMD Proj	"Freddy's…"	20.1±0.3	Freddy's. red	15.4±0.3	Reel 3D #1 cyan	2.92±0.04
Infocus 1DMD Proj	"DDD"	8.9±0.2	DDD red	4.1±0.1	Reel 3D #1 cyan	0.71±0.01
Epson 3LCD Proj	"DDD"	3.92±0.08	DDD red	1.89±0.05	Reel 3D #1 cyan	0.324±0.005
VT2 3LCD Proj	"DDD"	4.66±0.09	DDD red	2.75±0.06	Reel 3D #1 cyan	0.408±0.007
VT6 3LCD Proj	"DDD"	3.93±0.08	DDD red	2.45±0.06	Reel 3D #1 cyan	0.427±0.007
Boxlight2 3LCD Proj	"Reel 3D #1"	3.08±0.06	DDD red	1.63±0.04	Reel 3D #1 cyan	0.480±0.008
Boxlight3 3LCD Proj	"3DG 11"	4.59±0.09	DDD red	2.57±0.05	Reel 3D #1 cyan	1.44±0.02

3.4 Validation

To check that the results from the crosstalk model were sensible, a first order validation test was performed using a CRT display. A pair of rectangles, one red (R=255, G=B=0), one cyan (R=0, G=B=255), which shared an edge were displayed on a CRT screen. An anaglyph filter was held over the intersection. Ideally, if the filter was red, the red half would be bright red and the cyan half would be black (or vice versa for a cyan filter). To a first order approximation, the closer the complimentary side of the filter was to black, the lower the expected percentage crosstalk through that filter.

The model takes into account the brightness of the transmitted colour too, which can also be roughly guessed by the eye. The validation involved holding up two filters of the same colour (eg red) at the same time, and seeing which had a blacker complimentary colour, and how bright the matching colour was, and then estimating which pair of glasses would have a lower % crosstalk. Some filters were very easy to rank, eg the red 3DG18 (19.5±0.3%), 3DG02 (46.9±0.7%) and 3DG04 (60.5±0.8%). The eye's first order observations agree reasonably well with the model being used except where the % crosstalk difference was <2% at which point many of the glasses were difficult to arrange into sequence by eye anyway. One characteristic the eye has, that the model does not, is the tendency for some colours to seem brighter or dimmer than they really are when placed near certain other colours.[9] Perhaps this effect distorts perceived brightness enough to overwhelm small differences in crosstalk.

4. DISCUSSION

It is worth mentioning that even a perfect filter (one that transmits 100% of light in the desired wavelength domain and 0% outside it) will have crosstalk if the display's green channel spectral output, say, overlaps the filter's red domain. Hence the perceived crosstalk will vary between display devices, even for the same pair of filters. Glasses will generally produce low ghosting figures if the filters have a low crossover point as well as ≈0% transmission outside their desired wavelength region. The wavelength of the crossover point is also important - Ideally, the wavelength of the glasses' crossover point will be close to that of the display device's crossover point.

When choosing a display and filter combination, several aspects must be considered. Firstly, large amounts of crosstalk degrade the quality of the 3D experience, and the images become more difficult for the brain to fuse. This project aimed to highlight possible low-crosstalk combinations, so crosstalk could be reduced. Secondly, intensity is important. If the filter cuts out most of the light, the image will be very dim and hard to see. Lower light levels also make the effect of even small ghosting levels proportionally greater than they might otherwise be. A brightness imbalance between left and right eye can also result in the Pulfrich effect whereby horizontal motion can be interpreted as binocular depth – which is generally undesirable. Brightness levels and imbalance have not been considered in this paper.

Thirdly, colour must be considered. Truly full colour stereoscopic images are not possible with anaglyphs, but a properly constructed anaglyph using complimentary colours can approximate a full colour image. This distorted colour image is usually referred to as a "pseudo-colour anaglyph" or a "polychromatic anaglyph" rather than a "full colour anaglyph". If a non-complimentary combination is used, (e.g. red/blue or red/green) pseudo-colour anaglyphs are impossible, as a large portion of the visible spectrum is missing. The overall image may also be darker. This paper has only considered red/cyan anaglyphs.

For red/cyan anaglyphic 3D images, the minimum overall crosstalk factor in CRTs was very high at 22.5±0.3. Even mixing and matching the best filters would only reduce the crosstalk factor to just over 21. This is despite the fact that many of the glasses tested were specifically made for watching 3D videos on television CRT screens. The main difficulty here is not the filters, but the large overlapping wavelength domains of the CRT phosphors. This could be reduced by using red/blue only anaglyphs on CRTs, since the crosstalk factor for them decreases to 5.89±0.09, but this entails other problems as discussed in the previous two paragraphs. The Acer Laptop LCD that was tested has very high crosstalk factors with all tested glasses. Again, there is little a filter can do when the spectral output of the display device is active across so many different wavelengths; Figure 3 shows that when showing a red screen only, for example, the output includes wavelengths all the way into the blue region. It would be near impossible to obtain a filter that matches well with this output. 3-chip LCD projectors exhibited the lowest overall crosstalk factor of all the displays tested. Single chip DMD based projectors (NEC3 and Infocus) gave crosstalk results that were worse than 3-chip LCD projectors but better than CRT displays. These variations between displays are understandable given that each of the different technologies (CRT, LCD, LCD projector, and DMD) use different methods to create the three colour primaries.

We have defined a cyan filter as one that passes a reasonable amount of blue and green (but very little red). If the filter passes blue but very little green and red, it is considered a blue filter. We realise this definition is somewhat approximate – to be more scientific the relative transmission of each of the colour primaries through the filters could be calculated and the filters classified on this bases. This data would also be useful for evaluating the colour balance of the image for image quality purposes and evaluating possible Pulfrich effects. It is also worth noting that the colour balance of the display will also have an effect on ghosting. It can be seen that a slight colour balance difference between Boxlight2 and Boxlight3 has produced a different set of ghosting results (see Figure 4 and Table 3). In this study we have used the default colour balance of the display, however colour balance effects could also be studied in more detail.

It should be noted that this study only reports on emissive displays. Some of the glasses were intended for use with printed anaglyphs, and hence may perform better with printed anaglyphs than emissive displays. However, testing of anaglyphic 3D ghosting with printed anaglyphs is not reported here.

5. CONCLUSION

This study has revealed that crosstalk in anaglyphic 3D images can be minimised by the appropriate choice of anaglyphic 3D glasses. The study has revealed that there can be considerable variation in the amount of ghosting present when an anaglyphic 3D display is viewed with different anaglyphic 3D glasses.

The study has also revealed that there is considerable variation in the amount of anaglyphic ghosting exhibited by different types of displays – 3 chip LCD projectors were found to offer considerably lower anaglyphic ghosting than the other types of displays tested in this study (CRT displays, LCD screens, and DMD projectors).

The anaglyphic ghosting model works well and generates outputs which appear to agree with subjective assessments of anaglyphic 3D ghosting. The model currently does not take into account the more complicated aspects of colour vision, such as hue perception. However as technological advances, such as functional MRI, are increasing our ability to understand the anatomy, physiology and perception of colour, and non-linear modelling continues[9], when a complete model is perfected and agreed upon, the program can be modified to include it. The model also does not take into account dimness, brightness imbalance, or pseudo-colour considerations, which are also important to the anaglyph 3D experience.

It should be noted that the results of this paper are not intended to be a leaderboard of one glasses manufacturer versus another - we haven't tested all glasses from all manufacturers, nor have we tested a large sample of each manufacturers glasses. This paper does however highlight that there is significant variation between different anaglyph 3D glasses and displays. Further crosstalk optimisation may be possible by using the model and working with 3D glasses manufacturers.

REFERENCES

1. Tan, Stanley (2001), *Sources of Crosstalk in 3D Stereoscopic Displays*, Centre for Marine Science & Technology, Curtin University of Technology, Bentley, Western Australia.
2. Woods, Andrew & Tan, Stanley (2002), "Characterising Sources of Ghosting in Time- Sequential Stereoscopic Video Displays", presented at *Stereoscopic Displays and Applications XIII*, published in *Stereoscopic Displays and Virtual Reality Systems IX*, Proceedings of SPIE Vol. 4660, pp. 66-77, San Jose, California, 21-23 January 2002.
3. Konrad, J (2000), "Cancellation of image crosstalk in time-sequential displays of stereoscopic video", in *IEEE Transactions on Image Processing*, Vol. 9, No. 5, pp 897–908.
4. Sanders, William & McAllister, David (2003) "Producing Anaglyphs from Synthetic Images", presented at *Stereoscopic Displays and Applications XIV*, published in *Stereoscopic Displays and Virtual Reality Systems X*, Proceedings of SPIE Vol. 5006, pp 348-358, Santa Clara, California, 21-23 January 2003.
5. Lovy, D (1996), *WINDIG 2.5*, Email: lovy@scsun.unige.ch, Dept of Physical Chemistry, University of Geneva, Switzerland.
6. Hollins, Martin (1990) *Medical Physics*, Thomas Nelson & Sons, London, pp26-27.
7. MacDonald & Burns (1975) *Physics for the Life and Health Sciences*, Addison Wesley, USA.
8. Ohno, Yoshi (1999), *OSA Handbook of Optics, Volume III: Visual Optics and Vision*, National Institute of Standards and Technology, Maryland USA.
9. Connolly, C (2003), "Colorimetry: Anatomical Studies Advance", *Photonics Spectra*, Issue Aug 2003, pp 56-66.
10. *HCinema* (not dated), [online], Available: http://www.projektoren-datenbank.de/pro [accessed 21st Dec 2003] "Projektoren-Datenbank", "Abkurzungen", "Lexikon", "DLP Projektoren", "LCD Projektoren".