How are Crosstalk and Ghosting defined in the Stereoscopic Literature?

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ABSTRACT

Crosstalk is a critical factor determining the image quality of stereoscopic displays. Also known as ghosting or leakage, high levels of crosstalk can make stereoscopic images hard to fuse and lack fidelity; hence it is important to achieve low levels of crosstalk in the development of high-quality stereoscopic displays. In the wider academic literature, the terms crosstalk, ghosting and leakage are often used interchangeably and unfortunately very few publications actually provide a descriptive or mathematical definition of these terms. Additionally the definitions that are available are sometimes contradictory. This paper reviews how the terms crosstalk, ghosting and associated terms (system crosstalk, viewer crosstalk, gray-to-gray crosstalk, leakage, extinction and extinction ratio, and 3D contrast) are defined and used in the stereoscopic literature. Both descriptive definitions and mathematical definitions are considered.

Keywords: stereoscopic, crosstalk, cross talk, cross-talk, ghosting, leakage, extinction, 3d contrast.

1. INTRODUCTION

Crosstalk (sometimes also known as ghosting or leakage) is a critical factor affecting the image quality of stereoscopic 3D displays. Crosstalk is the incomplete isolation of the left and right image channels so that one image leaks into the other. This paper reviews the literature on crosstalk and related terms in stereoscopic displays and provides a useful basis for the understanding, further analysis and standardization of the terminology relating to 3D crosstalk. Crosstalk is present in most stereoscopic displays and is often the most important factor affecting the 3D image quality.

To have a constructive discussion about crosstalk, it is necessary to have a common understanding. Surprisingly, very few early papers actually define crosstalk and related terms when they are discussed, many papers use crosstalk and ghosting interchangeably, and even where there are definitions, the definitions are not always consistent between papers.

This paper is related to an earlier paper which reviewed the definition, measurement and mechanisms of crosstalk[1] but this paper focuses more on the definitions given in the published literature.

Stereoscopic terminology can be used to describe a principle in general terms and can also be used to quantify a physical property – this paper will review both the descriptive and mathematical definitions where applicable.

To obtain an idea of the commonality of the various terms related to crosstalk across the stereoscopic literature, a keyword search was performed across the 1273 documents on the SD&A (Stereoscopic Displays and Applications) 20-year DVD-ROM[2] for various terms relevant to this paper. The results are detailed in Table 1. Importantly, the use of the term crosstalk is very common, present in over 10% of all stereoscopic documents in the collection.

2. TERMINOLOGY AND DEFINITIONS

2.1 Crosstalk - Descriptive Definition

The term 'crosstalk' (also often written as 'cross-talk'[3], 'cross talk'[24] or even 'X-talk'[3]) is very widely used in the stereoscopic literature (see Table 1). The term 'crosstalk' without an intermediate space or hyphen, is the more commonly used variant so that is what will be used in this paper. It is recommended that authors adopt this as the standard form.

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Table 1: Occurrence of stereoscopic terms across the 1273 documents in the SD&A 20-year DVD-ROM[2]

Crosstalk	125 documents with 1092 instances
Cross talk and Cross-talk	95 documents with 325 instances
Ghosting	117 documents with 589 instances
Ghost images	30 documents with 56 instances
Leakage	33 documents with 104 instances
Extinction	30 documents with 83 instances
Extinction Ratio	11 documents with 28 instances
3D Contrast	1 document with 30 instances

The term crosstalk has been described variously – here are some examples:

Lipton (1987)[5]: "Incomplete left and right channel isolation, or *crosstalk*, is of great concern to the designer of a stereoscopic system."

Veron, et al (1990)[6]: "The phenomenon of "bleed through" occurs when the left eye also sees the right image, or vice versa. Bleed through is also referred to as optical *crosstalk* between the two images. The metric that characterizes this phenomena is called the interocular *crosstalk* ratio."

Montgomery, et al (2001)[7]: "*Cross talk* represents *leakage* of the left eye image data to the right eye and vice versa as a fraction of the window brightness."

Stevenson, et al (2004)[8]: "3D *crosstalk* is a measure of how much of the left eye image gets into the right eye and vice versa."

Stevens (2004)[9]: "*Cross-talk* … describes the *leakage* of the optical signal in one channel of the viewing pupil to an adjoining channel"

Kaptein, et al (2007)[10]: "imperfect separation of the left and right images, a phenomenon known as *crosstalk*"

Pala, et al (2007)[11]: "optical *crosstalk* … is *leakage* of the optical signal from the channel corresponding to the right eye to the channel corresponding to the left eye and vice versa."

Uehara, et al (2008)[12]: "3D *crosstalk* is defined as the *leakage* of left-eye image to the right eye and vice versa, and is calculated as the ratio of luminance profiles."

Lipton (2009)[28]: "*Crosstalk*. Incomplete isolation of the left and right image channels so that one leaks (*leakage*) or bleeds into the other."

Despite some variations in wording, there is a common theme across these definitions – i.e. the light from one image channel leaking into another.

The terms '3D crosstalk' and 'interocular crosstalk' are also sometimes used but they are usually synonymous with 'crosstalk'.

The following dictionary definition "Cross-talk: unwanted interference between two neighbouring electronic circuits"[44] is not inconsistent with the definitions quoted above.

In this paper the following descriptive definition will be used (based on Lipton 2009):

***Crosstalk**: the incomplete isolation of the left and right image channels so that one image leaks into the other.*

2.2 Ghosting

In the general stereoscopic literature and the lay media, the terms 'crosstalk' and 'ghosting' have often been used interchangeably[24][25][26][27], but in scientific discussion, it is worthwhile to differentiate these terms.

Crosstalk and ghosting appear to have been first documented as separate terms in 1987 by Lenny Lipton: "If the left eye, for example, also sees the right there will be a *perceived* doubling of the image or "*ghosting*." Incomplete left and right channel isolation, or *crosstalk*, is of great concern to the designer of a stereoscopic system"[5]

In 2009, Lipton[28] provided a more formal definition of the two terms: "Crosstalk. Incomplete isolation of the left and right image channels so that one leaks (leakage) or bleeds into the other. Looks like a double exposure. Crosstalk is a physical entity and can be objectively measured, whereas ghosting is a subjective term." and "Ghosting. The perception of crosstalk is called ghosting."

'Ghost', 'Ghost Image' and 'Ghosting' have all been used in the stereoscopic literature and are usually used in the context of the perception of crosstalk.

2.3 Leakage

A formal definition for the term "leakage" was not found in the stereoscopic literature as part of this study, however the term is often used within descriptive definitions of "crosstalk"[7][9][11][12][28] (as summarized in Section 2.1). The Macquarie dictionary definition of "leakage" is "1. the act of leaking; leak. 2. that which leaks in or out. 3. the amount that leaks in or out."[44] Without a formal definition of leakage in the stereoscopic literature, it therefore seems appropriate to provide the following definition:

***Leakage**: the (amount of) light that leaks from one stereoscopic image channel to another.*

The term 'crossover contribution' has also been used.[45]

Contrary to this definition: Bos[46] used the term 'cell leakage ratio' but it was undefined in the paper and by usage it appears very similar to what most papers call crosstalk. Walworth, et al[47] used the sentence "visible leakage is least at 560 nm and no more than 0.2% in the red and blue regions" but this usage appears to be the same as the term crosstalk defined above.

2.4 Crosstalk - Mathematical Definition

Crosstalk can also be used as a metric to express how much crosstalk occurs in a particular stereoscopic display system. When expressed as a metric, 'crosstalk' is sometimes called 'crosstalk ratio'.[6][11] There are two mathematical definitions of crosstalk ratio which will be explained below, so when quoting crosstalk values it is important to specify which crosstalk definition is being used. Unfortunately several papers have quoted values of crosstalk without specifying the actual crosstalk definition they are using.[3][8][13][14][15]

Definition 1:

In its simplest form crosstalk can be defined[16] as:

$$\text{Crosstalk (\%)} = \text{leakage} / \text{signal} \times 100 \quad (1)$$

Where: 'leakage' is used here to mean the maximum luminance of light that leaks from the unintended channel to the intended channel, and 'signal' is the maximum luminance of the intended channel.

In practice, two luminance measurements are taken (from the intended eye position): (a) black in the intended channel and white in the unintended channel (this corresponds with leakage), and (b) white in the intended channel and black in the unintended channel (this corresponds with signal).

The following two mathematical definitions of crosstalk from the literature essentially agree with this basic definition:

Chu, et al[17] define:

$$\text{Crosstalk} \equiv \text{luminance measured at one eye} / \text{luminance measured at the other eye} \quad (2)$$

Note that this definition has been developed for a two-view autostereoscopic display and unfortunately uses rather imprecise language. A close look at the paper suggests that they actually mean "luminance of the other channel at the original eye position" for the denominator of (2).

Hong, et al[18] provides this definition in the context of a micropolarized display: "one test image consists of black data for the even horizontal lines and white data for the odd horizontal lines" (equating to black in the intended eye and white in the unintended eye) … "the other test image of black data for the odd horizontal lines and white data for even

horizontal lines" (equating to black in the unintended eye and white in the intended eye) … "The ratio of the measured luminance using these two test images corresponds to 3-D crosstalk."

The shortcoming of these definitions is that they don't include the effect of black level. Some displays are incapable of outputting zero luminance for full black (e.g. LCDs[†]) and other displays which can output zero luminance (e.g. CRT, PDP, and OLED displays[†]) might be incorrectly calibrated such that zero pixel value does not output zero luminance. The presence of non-zero black level does not contribute to visible crosstalk / ghosting and if present it would bias the crosstalk calculation using this first definition. If the black level is set at zero luminance, there would be no problem.

Definition 2:

The second mathematical definition of crosstalk takes into consideration non-zero black level by subtracting the black level luminance:

$$\text{Crosstalk (\%)} = (\text{ leakage} - \text{black level }) / (\text{ signal} - \text{black level}) \times 100 \tag{3}$$

Several papers support this formulation (but with different variable names):

Pala, et al[11] wrote: "In this work we define the optical crosstalk C as follows.

$$C = \frac{L_G - L_{BL}}{L_M - L_{BL}} \times 100 \tag{4}$$

Where L_M = Luminance of main image, L_G = Luminance of crosstalk (ghost) image, L_{BL} = LCD background luminance"

Liou, et al[19] provide the following equations:

$$\text{CL} = \frac{BW - BB}{WB - BB} \quad \text{and} \quad \text{CR} = \frac{WB - BB}{BW - BB} \tag{5,6}$$

Where: "WB = a video stream with all white as left-eye images, and all-black as right-eye images, BW = a video stream with all-black as left-eye images and all-white as right eye images, BB = a video stream with all-black for both left and right eyes (i.e. the black level of the display), and CL and CR = the crosstalk experienced by the left eye and the right eye." [19]

Boher, et al[20] also provide similar equations (reworked here for clarity and also note that the numerator of (8) has been corrected[21]):

$$\chi_L = \frac{Y^{GL}_{LKRW}(\theta_L,\varphi_L) - Y^{GL}_{LKRK}(\theta_L,\varphi_L)}{Y^{GL}_{LWRK}(\theta_L,\varphi_L) - Y^{GL}_{LKRK}(\theta_L,\varphi_L)} \quad \text{and} \quad \chi_R = \frac{Y^{GR}_{LWRK}(\theta_R,\varphi_R) - Y^{GR}_{LKRK}(\theta_R,\varphi_R)}{Y^{GR}_{LKRW}(\theta_R,\varphi_R) - Y^{GR}_{LKRK}(\theta_R,\varphi_R)} \tag{7,8}$$

Where: "3D crosstalk of right and left eyes χ_R and χ_L" and "(θ_R, φ_R) and (θ_L, φ_L) are the right and left eye positions in polar coordinates with regards to the measurement location". "Y_{KLRW} is the luminance for white view on right eye and black view on left eye, $Y^{GL}{}_{LWRK}$ and $Y^{GR}{}_{LWRK}$ are the luminances for black view on right eye and white view on left eye using GL and GR filters respectively, $Y^{GL}{}_{RKLK}$ and $Y^{GR}{}_{RKLK}$ are the luminance for black view on both eyes"[20]

Additionally, Weissman, et al[45] use a different technique to obtain a similar result:

$$CT_{RL} = (O_{GL} - O_{BL}) / (O_{WL} - O_{BL}) \quad \text{and} \quad CT_{LR} = (O_{GR} - O_{BR}) / (O_{WR} - O_{BR}) \tag{9,10}$$

Where: CT_{RL} is crosstalk from right channel to left channel (modified here for clarity), O_{GL} is the luminance of the ghost image (black in the left eye and white in the right eye) as measured from the left eye position, O_{BL} is the luminance of the black level as measured from the left eye position, O_{WL} is the luminance of white in the left eye and black in the right eye as measured from the left eye position, and so on.

This definition is sometimes called 'black-white crosstalk' since it uses full-black and full-white images in the testing scheme.[22] Full-white and full-black are used because maximum ghosting usually occurs when the pixels in the desired eye-channel are full-black and the same pixels in the opposite eye-channel are full-white.

[†] LCD = Liquid Crystal Display; CRT = Cathode Ray Tube; PDP = Plasma Display Panel; OLED = Organic Light Emitting Diode.

Crosstalk can initially be thought of as a fairly simple concept but now things start to get more complicated. On some displays crosstalk can vary with: (a) pixel position on the screen, (b) viewing angle (as expressed in equations (7,8)[20])[23], and (c) properties of the eyewear.

In most 3D displays crosstalk is an additive process and is roughly linear. The maximum leakage usually occurs in high-contrast (black/white) areas so measuring black-white crosstalk often determines the display's overall crosstalk, but, this is not true for all 3D displays, particularly time-sequential 3D on LCDs using active-shutter glasses, or PDPs, and perhaps other stereoscopic displays. This is discussed further in Section 2.6.

2.5 System Crosstalk and Viewer Crosstalk

In 2000, Kuo-Chung Huang, et al[29] defined two new terms (System Crosstalk and Viewer Crosstalk) in an attempt to disambiguate the terminology relating to crosstalk at that time:

> ***System Crosstalk****: the degree of the unexpected leaking image from the other eye.*
>
> ***Viewer Crosstalk****: the crosstalk perceived by the viewer.*[30]

It is important to note that System Crosstalk is independent of the content (determined only by the display), whereas Viewer Crosstalk varies depending upon the content.

These definitions have similarities to the definitions of Crosstalk and Ghosting provided by Lipton[28] – but are not exactly the same. The definition of Viewer Crosstalk includes the effect of contrast (and indirectly the effect of parallax) but Lipton's definition of ghosting includes any perception effect.

Mathematical definitions were also provided[29]:

$$\text{System Crosstalk (left eye)} = \beta 2 / \alpha 1 \tag{11}$$

Where: "α1 describes the percentage part of the left-eye image observed at the left eye position", and "β2 describes the percentage part of the right-eye image leaked to the left-eye position"[29] and vice versa for the other eye.

Viewer Crosstalk is "defined as the ratio of the luminance of unwanted ghost image, which leaks from the image for the other eye, to the luminance of the correct information received by the viewer's eyes." [29] i.e.

$$\text{Viewer Crosstalk (left eye)} = B\,\beta 2 / A\,\alpha 1 \tag{12}$$

Where: A is the luminance of a particular point in the left eye image, and B is the luminance of the same corresponding point (same x,y location on the screen) in the right-eye image.

The term Co-location Image Contrast was also introduced to describe the contrast between image points at the same (x,y) location on screen between the left and right eyes, and mathematically defined as:

$$\text{Co-location Image Contrast} = B / A \tag{13}$$

And hence:

$$\text{Viewer Crosstalk} = \text{Co-location Image Contrast} \times \text{System Crosstalk} \tag{14}$$

It is worth noting that equation (11) is similar to crosstalk definition 1 (equation (1)) in that it does not include the effect of black level, however black level is indirectly included in the definition of Viewer Crosstalk by way of the Co-Location Image Contrast term.

In 2009, Huang, et al[31] provided a revised definition of System Crosstalk which includes the effect of black level:

$$SCT_L = \frac{L_{KWL} - L_{KKL}}{L_{WKL} - L_{KKL}} \quad \text{and} \quad SCT_R = \frac{L_{WKR} - L_{KKR}}{L_{KWR} - L_{KKR}} \tag{15}$$

Where: SCT_L and SCT_R are the system crosstalk for the **l**eft and **r**ight eyes, L_{KWL} is the luminance measured from the **l**eft eye position with blac**k** in the left eye image and **w**hite in the right eye image, and so on.

As a result of this change it is important to establish which definition of system crosstalk (2000 or 2009) is being used when it appears in a publication.

2.6 Gray-to-Gray Crosstalk

As mentioned in the end of Section 2.4, crosstalk occurs in some displays (particularly time-sequential 3D LCDs) in a non-linear and non-additive fashion. The term 'gray-to-gray crosstalk' was therefore developed as a metric to quantify crosstalk in such displays. In essence gray-to-gray crosstalk is the matrix of values of crosstalk ratio for all gray level transition combinations on a display. On a display with linear crosstalk, all the values in the matrix would be the same, however with a 3D display which exhibits non-linearity of crosstalk, the values in the matrix would be mostly different. In the case of time-sequential 3D LCDs, the non-linearity is due in part to the period of time that it takes an LCD pixel to transition from one gray level to another (the pixel response rate), and the fact that the pixel response rate is different for different gray level transitions (i.e. it is a matrix).

Surprisingly, the term gray-to-gray crosstalk was first introduced and defined by three separate papers[22][32][33] very recently at the same conference in May 2010. The three definitions are provided below:

Shestak, et al[22] defined:

$$C_l(q_1,q_2)=\frac{W_l(q_1,q_2)-W_l(q_1,q_1)}{W_l(q_2,q_2)-W_l(q_1,q_1)} \tag{16}$$

Jung, et al[32] defined:

$$CT_{i,j}=\left|\frac{G_{i,j}-G_{i,i}}{G_{j,i}-G_{i,i}}\right|\times 100[\%] \tag{17}$$

Pan, et al[33] defined:

$$C.T._{i\to j}=\frac{\left|L_{j\to j}-L_{i\to j}\right|}{L_{j\to j}-L_{i\to i}} \tag{18}$$

Where the variables are defined as follows:

Shestak (2010) Samsung, Korea[22]	Jung (2010) LG, Korea[32]	Pan (2010) Chi Mei Innolux, Taiwan[33]	Variable definitions:
q_1 and q_2	i and j	i and j	are the two specified gray levels between which the gray-to-gray crosstalk is being calculated/measured
$C_l(q_1,q_2)$ and $C_r(q_1,q_2)$	$CT_{i,j}$	$C.T._{i\to j}$	is the gray-to-gray crosstalk between the specified gray levels (for left (l) and right (r) eyes)
$W_l(q_1,q_2)$ and $W_r(q_1,q_2)$	$G_{i,j}$	$L_{i\to j}$	is the luminance measurement obtained when the two channels are set to the specified gray levels

The three equations are very similar and apart from minor differences such as the sign of the result, the use of percent notation and variable names, the only difference of significance is that the denominator in equation (17) is slightly different to the denominator of (16) and (18). Specifically, if the denominator in (17) was the same as (16) and (18) it would be written as " $G_{j,j}-G_{i,i}$ " rather than the existing " $G_{j,i}-G_{i,i}$ ". The existing arrangement of the denominator of (17) is similar in formulation to equations (5,6) used in the definition 2 of crosstalk. The significance of this difference is yet to be fully investigated.

Remembering that the mathematical definition of gray-to-gray crosstalk is a ratio, this formulation needs to be extended to determine the amount of visible crosstalk for different gray levels. The maximum visible crosstalk will not necessarily occur at the same gray levels as the maximum gray-to-gray crosstalk since the co-location image contrast also needs to be considered. To date the extension of 'gray-to-gray crosstalk' to 'gray-to-gray visible crosstalk' does not appear to have been published.

If you wish to use these equations to relate pixel gray level to display luminance, it will be necessary to consider gamma and the calibration of the display.[45]

2.7 Extinction and Extinction Ratio

The terms extinction and extinction ratio are not used as commonly in the stereoscopic literature as the term crosstalk (ref. Table 1) but nevertheless it is an important concept. 'Extinction' and 'extinction ratio" are commonly used without definition however some meaning can often be gained from the context of usage – for example:

Hines (1984)[34]: "The polarizing filters should be chosen to give a high extinction ratio. Polaroid's HN-38 material works quite nicely with a ratio of 600:1, and their more expensive HN-38s material has a ratio of 2000:1."

Walworth, et al (1984)[35]: "Circularly polarized light provides efficient extinction over a wide range of angular rotation"

Haven (1987)[36]: "extinction ratio measurements made from 470 to 630 nanometers varied between 20:1 and 35:1."

Lipton (1991)[37]: "In practice it is possible to closely approach the extinction ratio of the polarizer, which can be 2000:1."

In the stereoscopic literature, 'extinction' usually refers to the process or concept of extinction and 'extinction ratio' usually refers to the metric or measurement of extinction – although this distinction should be obvious from the usage.

Some explicit mathematical definitions were found in the stereoscopic literature:

Yeh, et al (1987)[38]: "Crosstalk was defined by the extinction ratio between the left- and right-eye images and was measured as the ratio of the luminance of the correct eye image to the luminance of the unwanted "ghost" from the image intended for the opposite eye. The higher the extinction ratio, the less the "ghosting" surrounding the stereo images."

Hodges (1991)[39]: "extinction ratio (the luminance of the correct eye image divided by the luminance of the opposite eye ghost image)"

Abileah (2011)[40] defines 'extinction ratio' as:

$$X_1 = \frac{L_{1wk}}{L_{1kw}} \quad \text{and} \quad X_2 = \frac{L_{2kw}}{L_{2wk}} \tag{19,20}$$

Where: X_1 and X_2 are the extinction ratio for the left and right eye views, L_{1wk} is the luminance measured from the left eye position with white in the left eye image and black in the right eye image, L_{1kw} is the luminance measured from the left eye position with black in the left eye image and white in the right eye image, L_{2kw} is the luminance measured from the right eye position with black in the left eye image and white in the right eye image, and L_{2wk} is the luminance measured from the right eye position with white in the left eye image and black in the right eye image.

The Yeh definition includes mention of crosstalk but this is inconsistent with other definitions and must be an error. Although the Yeh and Hodges definitions don't specify the use of maximum (full-white) test signals for correct eye image and ghost image, it is probably fair to assume this. Apart from these two points, the three definitions of extinction ratio are consistent with each other.

Two important points are worth noting here. Firstly, these definitions do not include the effect of black level. High black levels would adversely bias the extinction ratio value using these definitions. Secondly, these definitions of extinction ratio equate to the inverse of crosstalk ratio (definition 1).

2.8 3D Contrast and Stereo Contrast Ratio

Definitions for '3D contrast' and 'stereo contrast ratio' were found in the stereoscopic literature as follows:

Boher, et al[20] define '3D contrast' as:

$$C_L = 1 / \chi_L, \quad C_R = 1 / \chi_R \quad \text{and} \quad C^{3D} = (C_R \times C_L)^{0.5} \tag{21,22,23}$$

Where: C_L and C_R are 3D contrast for the left and right eyes as viewed through the left and right filters, χ_L and χ_R is the 3D crosstalk for left and right eyes (see equations (7,8)), and C^{3D} is the combined 3D contrast for both eyes. Note

that the variable name C in equations (21,22,23) is used for contrast whereas C is used for crosstalk in most other stereoscopic papers.

Abileah (2011)[40] defines 'stereo contrast ratio' as:

$$CR_1 = \frac{L_{1ww}}{L_{1kk}} \quad \text{and} \quad CR_2 = \frac{L_{2ww}}{L_{2kk}} \tag{24,25}$$

Where: CR_1 and CR_2 are 'stereo contrast ratio' for the left and right eyes, L_{1ww} is the luminance measured from the left eye position with white in the left eye image and white in the right eye image, and so on.

These two terms '3D contrast' and 'stereo contrast ratio' seem very similar by name, but are functionally very different. The definition of '3D contrast' is the inverse of definition 2 of crosstalk ratio (see equation (3)), whereas the definition of 'stereo contrast ratio' is essentially the contrast ratio of one channel biased by the amount of crosstalk between channels.

2.9 Other Definitions

Shestak, et al[22] provide equations for dark crosstalk and light crosstalk specifically relating to crosstalk in time-sequential 3D on LCDs:

$$\text{Dark crosstalk: } C^{dark} = (W'_2 - W_2) / (W_1 - W_2) \tag{26}$$

$$\text{Light crosstalk: } C^{light} = (W'_1 - W_1) / (W_2 - W_1) \tag{27}$$

Where: W_1 and W_2 are the original desired luminance for points in the left and right eye view (W_1 is the lower of the two luminances), W'_1 is the displayed luminance affected by crosstalk which brightens the image, and W'_2 is the displayed luminance affected by crosstalk which darkens the image.

Uehara, et al[41] have investigated crosstalk in multi-view autostereoscopic displays and attempt to make a distinction between 'interocular crosstalk' and (for the lack of better term) 'adjacent-view crosstalk'. In a multi-view autostereoscopic display, the left and right eyes may not be in adjacent views – for example the left eye might see view number 4 and the right eye might see view number 7. A small amount of crosstalk between adjacent views ('adjacent-view crosstalk') (e.g. view 4 and 5) can be desirable since it reduces the visibility of the transition as the eye moves between views[42], however any crosstalk visible between the two views in which the two eyes are located ('interocular crosstalk') (e.g. view 4 and view 7 in the example above) is undesirable. The mathematical definition of crosstalk used by Uehara, et al[41] is equivalent to crosstalk definition 1. In another paper, Uehara, et al[43] use the term '3D crosstalk' instead of the term 'adjacent-view crosstalk' defined here, however this should be avoided because the term '3D crosstalk' is used in some other papers as synonymous to regular 'crosstalk'.

Chang, et al[3] describe 'dynamic crosstalk' (of moving images) as distinct from the other formulations which are assumed to be 'static crosstalk'.

The term 'crosstalk' is also used in the electronic communications field to refer to the leakage of a signal between one communications channel and another. An attempt was made to find a concise definition of crosstalk from this field for this study but was unsuccessful.

3. DISCUSSION

There is a definite need to standardize the terminology and definitions relating to crosstalk in stereoscopic displays. This paper has revealed considerable variation between definitions in various papers which is detrimental to the ongoing discussion and research of this topic.

There is also a level of ambiguity of language when people talk or write about crosstalk. Are they meaning crosstalk generally? Are they referring to crosstalk ratio? Are they really talking about visible crosstalk or ghosting? Sometimes the context will reveal the meaning, but particularly in written form it is important to use the language of crosstalk carefully and define or specify the meanings being used or refer to a standard.

A major inconsistency found in this study is the differing handling of display black level in the crosstalk ratio and extinction ratio calculations. Displays are trending towards lower black levels which may reduce this discrepancy, however the crosstalk ratio of high-quality displays are also reducing, which will amplify the discrepancy.

It would be worth having a considered discussion about whether the effect of non-zero black level should be included or removed from the mathematical definition of crosstalk ratio – i.e. should definition 1 or definition 2 be used moving forward.

It would be worth analyzing the effect of non-zero black level of current displays on the results of using these definitions to determine how significant the effect is.

The brightness and contrast settings on a display may affect the measurement of crosstalk and would probably need to be calibrated before conducting testing – particularly for the use of test charts to measure crosstalk[45] and the measurement of gray-to-gray crosstalk.

It is not only important to provide standardized descriptive and mathematical definitions – it is also important to define standardized techniques of measuring these important 3D display quality parameters.

There are a number of standardization efforts underway at the time of writing this paper which may address some of the terminology and definition problems identified in this paper. Activities include:

- The ICDM (International Committee on Display Metrology) (part of SID) is currently working on the "Display Measurements Standard" of which version 1.0 is expected to be released mid-2011. This standard will include a section on 3D display measurement standards.
- The IEC (International Electrotechnical Commission) has established technical committee TC110 (Flat Panel Display Devices) to establish standards relating to "optical measurement methods for 3D displays". This work includes some coverage of crosstalk measurement.
- The SEMI (Semiconductor Equipment and Materials International) has been working on a document "3D Display Terminology" which includes some definitions of crosstalk related terms.

It will be worth watching for the results of these standardization efforts.

Lastly an open question: How should crosstalk be measured in 3D display systems employing crosstalk cancellation[1]? Should the crosstalk cancellation be turned off before conducting the measurements or should it be left on? What if the crosstalk cancellation cannot be turned off? In cases where crosstalk cancellation is used, crosstalk will still be present but ghosting may not be visible.

4. TERMINOLOGY SUMMARY

This paper has reviewed the historical meaning of a range of terms in the stereoscopic literature. A summary of descriptive definitions of various stereoscopic terms is offered here for clarity. The definitions provided here are by no means final and the author would welcome the further improvement of these definitions. One shortcoming of some of these definitions is that they may not be easily extensible to multi-view autostereoscopic displays.

***Crosstalk**: the incomplete isolation of the left and right image channels so that one image leaks into the other.*

***Crosstalk Ratio:** (specifically) the metric of crosstalk.*

***Ghosting:** the perception of crosstalk.*

***Leakage**: the (amount of) light that leaks from one stereoscopic image channel to another.*

***System Crosstalk**: in general terms the same as Crosstalk, but as a metric it specifies the degree of the unexpected leaking image from the other eye using one of two equations (11) or (15).[29][31]*

***Viewer Crosstalk**: a measure of the crosstalk perceived by the viewer. cf: ghosting. (See (14))*

***Extinction, Extinction Ratio:** a measure of how well the opposite view is blocked in a stereoscopic display; the inverse of crosstalk.*

***Gray-to-Gray Crosstalk:** the matrix of values of crosstalk ratio for all gray level transition combinations on a stereoscopic display.*

***Cross-talk, Cross Talk, X-talk, Interocular Crosstalk, 3D Crosstalk:** see/use Crosstalk.*

A summary of mathematical definitions is not provided here because there is too much variation in the current mathematical definitions and arbitrary choice of variable names to be able to logically recommend a preferred usage here, apart from saying that: (a) the choice of variable names should follow a logical pattern and avoid overlaps with similar variables in related areas, (b) metrics should account for the presence of display black level, and (c) the standardization of new definitions should take into consideration historical usage. Additionally I don't wish to cut across the results of the standardization efforts currently underway.

5. CONCLUSION

This paper has reviewed the descriptive and mathematical definitions of crosstalk and related terms (ghosting, leakage, system crosstalk, viewer crosstalk, extinction, extinction ratio, and 3D contrast) in the stereoscopic literature. The relatively new term "gray-to-gray crosstalk" has also been described.

The understanding/definition/measurement of crosstalk on 3D displays are all improving rapidly – spurred on by rapid development and deployment of 3D displays and related technologies.

This paper has revealed a high level of ambiguity in relation to the mathematical definition of the crosstalk and extinction terms, and the variables used in these definitions. A well-written and well-researched standard would provide significant benefit to the industry as a whole and the onward improvement of stereoscopic display quality.

Ultimately we need stereoscopic displays which have low crosstalk, and we need the terminology and standards to support that.

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