Reproducibility of crosstalk measurements on active glasses
3D LCD displays based on temporal characterization

Sylvain Tourancheau*,a, Kun Wang*,b, Jaroslaw Bulatc, Romain Coussaud, Marcus Barkowskyy

a Dept. of Information Technology and Media, Mid Sweden University, Sundsvall, Sweden
b NetLab: IPTV, Video and Display Quality, Acreo AB, Kista, Sweden
c Dept. of Telecommunication, AGH University of Science and Technology, Kraków, Poland
d IRCCyN (UMR CNRS 6597), Polytech’Nantes, University of Nantes, Nantes, France

ABSTRACT
Crosstalk is one of the main display-related perceptual factors degrading image quality and causing visual discomfort on 3D-displays. It causes visual artifacts such as ghosting effects, blurring, and lack of color fidelity which are considerably annoying and can lead to difficulties to fuse stereoscopic images. On stereoscopic LCD with shutter-glasses, crosstalk is mainly due to dynamic temporal aspects: imprecise target luminance (highly dependent on the combination of left-view and right-view pixel color values in disparity regions) and synchronization issues between shutter-glasses and LCD. These different factors influence largely the reproducibility of crosstalk measurements across laboratories and need to be evaluated in several different locations involving similar and differing conditions. In this paper we propose a fast and reproducible measurement procedure for crosstalk based on high-frequency temporal measurements of both display and shutter responses. It permits to fully characterize crosstalk for any right/left color combination and at any spatial position on the screen. Such a reliable objective crosstalk measurement method at several spatial positions is considered a mandatory prerequisite for evaluating the perceptual influence of crosstalk in further subjective studies.

Keywords: crosstalk, temporal measurements, stereoscopic displays, shutter-glasses, time-sequential

1. INTRODUCTION
Crosstalk is one of the main display-related perceptual factors degrading image quality and causing visual discomfort on 3D-displays. It is usually defined as “the incomplete isolation of the left and right image channels so that one image leaks into the other”. It can be due to many factors varying according to 3D display technologies and many definitions and terms have been proposed in literature over the past twenty years. Crosstalk manifests itself through visual artifacts such as ghosting, blurring, and lack of color fidelity and provokes general annoyance and visual discomfort. Depth perception can be affected as well; to some extent crosstalk can even lead to stereoscopic depth breakdown. Figure 1 illustrates ghosting for a simple stereoscopic pair. The ‘leaking’ of the right image in the left view and vice versa provokes the apparition of a double image. This phenomenon is particularly noticeable and annoying in disparity regions, i.e. when right and left images have different values.

One of the current projects of the Video Quality Expert Group (VQEG) is to standardize the viewing environment for 3D presentations. In this context, VQEG plans to perform a multi-laboratory evaluation of the objective and subjective measurement of crosstalk on stereoscopic displays. A primary goal of this project is to propose a fast and simple method of crosstalk measurement that provides reproducible results across different environments and laboratories. This paper present the results of a campaign of objective crosstalk measurements carried out in three different laboratories and involving similar and differing conditions. This campaign has been focused on time-sequential 3D liquid crystal displays (LCDs) using active shutter-glasses.

The rest of this document is organized as follows: Section 2 describes how crosstalk manifest itself on time-sequential stereoscopic LCDs and reviews existing crosstalk metrics in that context. Sections 3 presents the two measurements procedures used in this study and the various test conditions involved. Section 4 presents and analyzes the results of the measurements. Finally Section 5 discusses the obtained results and conclude the main points of the work.

* Corresponding author: sylvain.tourancheau@miun.se
Figure 1: Illustration of ghosting with a simple stereoscopic pair of images. (a) Left and right digital images sent to the stereoscopic visualization system. (b) Left and right views as measured through the complete visualization system (e.g. display and glasses if any). Four regions can be defined in that case. Regions I and III are the zones where right and left signal have the same value, while zones II and IV are the disparity regions where right and left signals are different.

2. CROSSTALK ON TIME-SEQUENTIAL STEREOSCOPIC LCDS

There are so far no standardized procedures concerning crosstalk measurements and crosstalk metric calculations. For two-view stereoscopic visualization systems, the crosstalk ratio is usually defined with respect to black and white input signal. A definition commonly used\textsuperscript{4,5,9} is:

\[
C^L = \frac{\bar{L}_{0,255}^L - \bar{L}_{0,0}^L}{\bar{L}_{255,0}^L - \bar{L}_{0,0}^L}, \quad C^R = \frac{\bar{L}_{0,255}^R - \bar{L}_{0,0}^R}{\bar{L}_{255,0}^R - \bar{L}_{0,0}^R}
\]

where \(C^L\) is the crosstalk in the left channel, defined as the ratio between the average luminance \(\bar{L}_{0,255}^L\), measured from left eye position when left input image is a full-white image (all pixels value is 0) and right input image is a full-black image (all pixels value is 255), and the average luminance \(\bar{L}_{255,0}^L\), measured from left eye position when left input image is a full-white image and right input image is a full-black image. Usually, but not always,\textsuperscript{4} the non-zero black level of stereoscopic displays is taken into consideration by subtracting the black level average luminance \(\bar{L}_{0,0}^L\) (i.e. the average luminance measured from left eye position when both left and right input image are full black images). The same definition applies for crosstalk in the right channel \(C^R\), with average luminance values measured from the right eye position.

Since crosstalk can be considered as an additive and linear phenomenon in most 3D-displays,\textsuperscript{4} the use of full-white and full-black images permits to measure conditions for which maximum crosstalk usually occurs and therefore provides a good estimation of display’s overall crosstalk. However, this is not true anymore for displays that exhibit non-linear and non-additive crosstalk. In particular on time-sequential stereoscopic liquid-crystal displays (LCDs) using active shutter-glasses, crosstalk is mainly due to temporal characteristics (response time and synchronization) of the system’s components (display and active shutter-glasses).\textsuperscript{10,11}

More precisely, the luminance emitted by pixels within a frame period is usually imprecise because of the slow response of the liquid crystal cells, or because of hardly controllable response-time reduction systems (which lead to luminance over- or under-shoots). This issue is hardly predictable and depends upon the combination of left-view and right-view pixel color values in disparity regions.\textsuperscript{12} Another cause of crosstalk comes from the synchronization between shutter-glasses and LCD: the shutter open-period cannot be equally synchronized with the whole display because of the temporal delay between first and last lines update. Displays enhancement functions such as back-light flashing can even make this problem worse.\textsuperscript{13}

Figure 2 illustrates how and why ghosting artifacts appear on time-sequential 3D-LCDs. For use for this purpose the simple example presented in Figure 1. Four different regions are defined: regions I and III are the
zones where right and left images have the same value, while zones II and IV are the disparity regions where right and left images are different. Figure 2a illustrates the display luminance for each of this four regions. In zone I (resp. zone III), both left and right images have the same value \(i\) (resp. \(j\)), the luminance measured on the display \(L_{i,i}^D(t)\) (resp. \(L_{j,j}^D(t)\)) in then a steady signal. In zone II (resp. zone IV), left and right image have different values and the luminance emitted by the display \(L_{i,j}^D(t)\) (resp. \(L_{i,j}^D(t)\)) alternates between \(i\) and \(j\) (resp. between \(j\) and \(i\)).

On time-sequential 3D-LCDs, right and left images are separated and guided to corresponding eyes thanks to active shutter-glasses synchronized with the display in order to be opened when the corresponding signal is displayed on the screen. Figure 2b: illustrates the temporal transmittance functions \(\tau_L(t)\) and \(\tau_R(t)\) of each shutter-glass. These transmittance functions are synchronized with the display luminance waveforms presented in Figure 2a. The luminance signal seen through each glass is then the result of the multiplication between the transmittance function of each shutter-glass and the display luminance, for example in region II:

\[
L_{i,j}^L(t) = \tau_L(t) \cdot L_{i,j}^D(t) \\
L_{i,j}^R(t) = \tau_R(t) \cdot L_{i,j}^D(t)
\]  

The resulting luminance waveforms measured through left glass \(L_{i,j}^L(t)\) and right glass \(L_{i,j}^R(t)\), in region II, are plotted in Figure2b and Figure2d, along with those corresponding to the other regions.

Finally, the average luminance level of region II as seen from each eye position is obtained by averaging the previous waveforms over a whole number of periods:

\[
\bar{L}_{i,j}^L = \int_{t_0}^{t_0 + N \cdot T} L_{i,j}^L(t) \cdot dt \\
\bar{L}_{i,j}^R = \int_{t_0}^{t_0 + N \cdot T} L_{i,j}^R(t) \cdot dt
\]  

Average luminance levels measured from each eye position for each region of the stereoscopic image are presented as a function of the horizontal axis in Figure3. It can be observed that these luminance levels are not necessarily identical from one eye position to the other due to slightly asymmetrical transmittance functions.

It is clear from this simple example that the ghosting occurring in time-sequential 3D-LCDs is mainly due to the failure of the display to reach the correct luminance level within the short frame period (8.33 ms for 120-Hz displays). Since the response time of display pixels depends highly upon the starting and ending levels of luminance, it is clear that the crosstalk metrics given by Equation 1 which concerns only the black and white combination cannot be representative of the overall crosstalk of the display. For this reason, several crosstalk metrics have been recently proposed in the literature.\(^{12,13,14,15,16}\) They propose to compute the crosstalk ratio for any combination \(\{i, j\}\) of left and right pixels values. These color values are usually grey values, i.e. each sub-pixels is submitted to the same digital input: \(R = G = B = i\) and \(R = G = B = j\). The crosstalk ratio is often referred to grey-to-grey crosstalk in that case. These crosstalk metrics are given here for a left-eye position, and original expressions have been adapted to follow the notations defined previously in this paper (average luminance levels depicted in Figure 3).

Pan et al.\(^{13}\) and Shostak et al.\(^{12}\) proposed two very similar definitions which consist of the ratio between the error of luminance and the amplitude of the considered grey-to-grey transition. The equations are respectively:

\[
C_{i,j}^L = \frac{\bar{L}_{i,i}^L - \bar{L}_{i,j}^i}{\bar{L}_{i,i}^L - \bar{L}_{j,j}^i} \quad (4)
\]

\[
C_{i,j}^L = \frac{\bar{L}_{i,i}^L - \bar{L}_{i,j}^L}{\bar{L}_{i,i}^L - \bar{L}_{j,j}^i} \quad (5)
\]
Figure 2: Luminance signals in the four regions defined in Figure 1. (a) Luminance measured directly on the display, the alternation between right and left values can be observed for regions II and IV (disparity regions). (b) Transmittance of the shutter-glasses as a function of time, synchronized with the display signal. (c-d) Luminance measured through the left and right shutter-glass respectively, the waveforms corresponds to the display luminance signals multiplied by the shutter-glass transmittance (cf. Equation 2).
Jung et al.\textsuperscript{14} proposed a similar definition, directly inspired from the black-white crosstalk defined in Equation 1. The difference with the two previous definitions comes from the denominator which in that case take into account the opposite combination (just as Equation 1 does):

\begin{equation}
C_{i,j}^L = \frac{|I_{i,j}^L - I_{i,i}^L|}{|I_{j,i}^L|}
\end{equation}

Finally, Bulat et al.\textsuperscript{16} defined grey-to-grey crosstalk directly as the relative error of luminance:

\begin{equation}
C_{i,j}^L = \frac{|I_{i,j}^L - I_{i,i}^L|}{I_{i,i}^L}
\end{equation}

It has been chosen here to keep using the term crosstalk as in previous literature even if in the case of time-sequential 3D-LCDs the main cause of ghosting is not a luminance leakage from one channel to another (as crosstalk is usually defined) but rather a failure of the display to reach correct luminance levels with respect to different conditions.

3. MEASUREMENTS

3.1 Conditions

As it has been shown previously, crosstalk on time-sequential 3D-LCDs is mainly due to the slow response time of the display when the luminance has to alternate between right and left value, and therefore is highly dependent upon the right-left combination of pixels values. In order to figure out how important are these crosstalk variations, it has been decided to conduct a fully comprehensive measurement campaign, testing all 65536 grey-to-grey combinations of the display. Moreover, these measurements have been performed at three different positions on the screen in order to study the influence of the synchronism between the shutter-glasses and the display.

Measurements have been conducted in three different laboratories:
- Lab1: Realistic3D Lab, Mid Sweden University (affiliation a on the first page)
- Lab2: NetLab, Acero AB (affiliation b)
- Lab3: IVC Lab, IRCCyN (affiliation c)

Two different measurement methods have been used in this study:

1. The first method consists in measuring luminance through the complete stereoscopic system (display and shutter-glasses) for different grey-to-grey combinations.

2. The second one consists in measuring the grey-to-grey temporal transitions of the display alone and then applying the transmittance functions of the shutter-glasses to obtain the luminance as seen from each eye-position (cf. Equation 2).

The first method present the inconvenience to be very sensitive to the measurement’s setup, to the position and orientation of the glasses, the measured field of view, etc. To properly handle these parameters, complex optical arrangements are necessary (e.g. Fabry assemblies) which are usually expensive and necessitate a complex expertise. Such a protocol does not fit the current VQEG requirements, that is to say to propose a fast and simple measurement protocol which could be easily carried out in various labs. The second method presents the advantage of requiring only close-contact measurements on the display: this kind of measurements is usually easier to carry out and less subject to variation from lab to lab. This method is similar to the one presented by Boher et al., except that their study used simulated display transitions for combinations of 9 grey levels while the work presented here uses real display measurements of all 65536 grey-to-grey combinations.

3.2 Equipment

3.2.1 Photo-diodes

Due to the dynamic nature of the problem, the proposed method consists in high sample-rate measurements of the temporal responses of both shutter-glasses and displays. For the reasons mentioned above, some close-contact instruments, that do not necessitate any optics assemblies, have been used. The three instruments are quite comparable to each other and based on fast photo-diode electronic circuits. Details are given here:

- Lab1: Siemens BPW21 silicon photo-diode. Response time: 25 µs for rise time, 41 µs for fall time.

Photo-diodes are housed in boxes to shield any ambient light and surrounded by black velvet in order to avoid any scratches to the display surface. Signals are captured by a dual-channel 12-bit USB oscilloscope (DS1M12 from EasySync Ltd.) with a sampling period of 20 µs.

3.2.2 Conversion to luminance

Voltage signals obtained from the photo-diodes are then converted into luminance values thanks to the following luminance-meters:

- Lab1: KonicaMinolta LS-110
- Lab2: Photo Research PR522/524
- Lab3: CRS Optical OP200-E
Conversion functions have been determined independently in each lab by measuring the steady luminance value of each of the 256 grey levels simultaneously with the photo-diode and the luminance-meter. These measures have been acquired in the center of the display, with and without shutter-glasses. Characteristics of the photodiodes have been found quite linear as expected and intermediate values have been interpolated easily to build three look-up-tables used to convert raw data from each lab. However, it must be mentioned here that the validity and the accuracy of this conversion is questioned for luminance values below 0.1 cd/m². Firstly because the luminance-meters that have been used are not accurate anymore in this range, and secondly because of the influence of the dark offset of the photo-diode.

In order to facilitate comparison between each lab, all results have been normalized with respect to the average luminance of the display measured in the center position for a combination of right and left full-white images (i.e. $L^D_{255,255}$). This permits to reduce possible variations due to the difference in the calibration of the three luminance-meters calibration, and to the differences of maximum luminance of the three display samples.

### 3.2.3 Stereoscopic system under test

Three different samples of the Alienware display OptX AW2310 have been measured. They have been used in their native resolution (1920 × 1080 pixels) with a refresh rate of 120Hz, together with PC equipped with NVIDIA 3D vision system (active liquid-crystal shutter-glasses). Stereoscopic images have been presented with Matlab and the PsychToolbox.

Display internal settings have been set identically in the three labs, and display have been turned on few hours before each measurements session.

### 3.3 Shutter-glasses temporal characterization

#### 3.3.1 Transmittance of shutter-glasses

To study the variability of the NVIDIA LC shutter-glasses used in this work, the transmittance functions of five shutter-glasses have been measured in Lab1. The luminance emitted by a white LED source have been measured through each glass of the five pairs. During these measurements, the photo-diode, the glass and the LED source have been aligned as close to each other as possible. The small size of the LED source permitted to keep a narrow field of view. Since these glasses used liquid crystal to block the light, the transmittance is very sensitive the polarization of the light. The light source used in these measurements was non-polarized, while the light emitted by a LCD is polarized by definition. In order to obtained transmittance values which correspond to the transmittance observed when the active glasses are used with the display under test, the waveforms have been scaled according the luminance ratios measured through the shutter-glasses with the luminance-meter. The same unique scaling function have been used for all pairs of shutter-glasses in order to keep the variability between samples. Each glass have been measured during 350 frames, and the waveforms corresponding to each period have been averaged together to reduce noise and potential variations. Figure 4 presents the transmittance of the right glass of each of the five pairs as a function of time with a logarithmic scale. It can be observed that the full width at the half height is about 2 ms, with an opening time of approximately 1.5 ms and a closing time of approximately 0.3 ms. These results are in concordance with those presented by Boher et al. Table 1 summarizes the maximum and average transmittance for each glass of the five pairs of shutter. The average transmittance is about 5.8% (i.e. maximum luminance seen through one glass is about 20 cd/m² for the display under test which has a maximum luminance of about 350 cd/m²), with a standard deviation of 0.26%.

<table>
<thead>
<tr>
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<td>#2</td>
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<tr>
<td>Maximum trans.</td>
<td>49.1</td>
<td>49.8</td>
<td>50.4</td>
<td>48.8</td>
</tr>
</tbody>
</table>

Table 1: Characterization of five different pairs of shutter-glasses.
3.3.2 Synchronization between the display and the shutter-glasses

In order to know the synchronism between display and shutter-glasses, the synchronization signal sent to the glasses by the infra-red emitter of the NVIDIA 3D Vision system has been measured. This sync signal has been acquired directly across the infra-red LEDs inside the emitter. Figure 5 illustrates the synchronism between this sync signal and the transmittance of the pair of shutter-glasses #1. In the following, the sync signal is measured simultaneously for all display measurements, in order to determine the synchronization between the display waveforms and the transmittance functions. Because of the top-to-bottom vertical scanning of LCDs, the opening period of the shutter-glasses is not equally synchronized with the display temporal responses. Figure 6 illustrates this difference for the three different measuring spots on the screen.

3.4 High-sample rate measurements

First method: display + shutter-glasses  The first method have been carried out only in Lab3. Measurements have been performed through the right glass for all combinations between 129 grey levels (from 0 to 254 with a step of 2, plus 255) in the center position, and for all combinations between 65 grey levels (from 0 to 252 with a step of 4, plus 255) in the top-left and bottom-right positions. A specific set-up has been designed in order to perform these measurements with a contact instrument: acquisition has been performed with the display lying flat, the photo-diode, the shutter-glass, and the display were aligned as close together as possible. Two small rings of non-reflective synthetic black foam rubber were disposed between the photo-diode and the shutter-glass and between the shutter-glass and the display in order to maintain a narrow measured field of view.

Second method: display alone + shutter-glasses simulation  The second method have been carried out in the three labs. All right and left combinations of the 256 grey levels have been measured in Lab1 and Lab2, for the three positions on the screen. Combinations between 65 grey levels (from 0 to 252 with a step of 4, plus 255) have been measured in Lab3, for the three positions on the screen. For each grey-to-grey combination, the synchronization signal have been acquired simultaneously. This synchronization signal has been afterward compared to the reference sync signal measured previously (cf. Section 3.3.2) in order to synchronize the transmittance functions of each shutter-glass with the display temporal responses and therefore obtained the luminance values as seen from each eye position, by the use of Equation 2.
Figure 5: Transmittance of left and right shutter-glasses and synchronization signal measured directly in the emitter across IR LEDs. Signals have been arbitrarily normalized between 0 and 1.

Figure 6: Synchronization between display and shutter-glasses for different positions on the screen. Waveforms have been measured for a combination $i = 0$ and $j = 255$, in the top-left position (a), in the center of the screen (b), and in the bottom-right position (c). Luminance of the display has been normalized with respect to the white luminance (measured for a combination $i = j = 255$). Transmittance functions of the shutter-glasses have been normalized between 0 and 1 for clarity.
Figure 7: Comparison of both measurement methods at three positions on the screen. Top row shows luminance measured with the first method at the right-eye position for three different positions on the screen. Bottom row shows luminance values obtained from the second method, i.e., by the multiplication of right-glass transmittance with luminance waveforms measured directly on the display.

For both methods, the final luminance waveforms (directly measured through the shutter-glass, or obtained by a simulation of the shutter-glass transmittance) are averaged over a whole number of periods to obtain the mean luminance as measured from each eye position. Finally, each grey-to-grey transition has been measured for a duration of 400 ms (48 frames, 24 frames for each view), i.e., 20000 samples. In average, it took around 1 second to measure one combination (overhead comes from data saving, oscilloscope commands sending and receiving, etc.) meaning that one complete measurement session took around 18 hours to measure the 65536 combinations at one position on the screen.

4. RESULTS ANALYSIS

4.1 Luminance

Final measurements results are obtained under the form of matrices presenting the luminance values seen from one eye position for combinations \{i, j\} of left and right values. Right values are varying horizontally and left values are varying vertically. If the stereoscopic visualization system was not suffering from crosstalk, all lines of the right-eye luminance matrices would be constant (no influence of the left value on the luminance corresponding to one given right value) and consequently all columns of the matrix would be similar. Similarly, on a perfect system the left-eye luminance matrices would have constant columns.

Figure 7 presents the luminance values measured at the right-eye position with both methods. It can be first observed that the results from both methods are very similar, particularly on top-left and center positions (linear correlation coefficients of 0.9939 and 0.9989 respectively). For bottom-right position, the difference is more important but the linear correlation coefficient is still high (0.9323): this difference might be due to a
Figure 8: Luminance measured at the left-eye position with the second method in the three different labs, for three positions on the screen.

luminance conversion problem (the conversion functions which have been used to convert voltage to luminance have been calibrated according to measurements performed in the center of the screen). Despite of these slight discrepancies, this result is a good evidence that the second method – which consists in simulating the action of the shutter-glasses on temporal waveforms measured directly on the display – permits to obtain results very similar to those obtained by measuring through the shutter-glasses, while using a much simpler set-up.

Figure 8 presents the luminance values measured at the left-eye position with the second method, for the three laboratories, and at three different positions on the screen. Here again, luminance matrices are very similar from one lab to another and it is clearly observed that the differences coming from the measuring position on the screen has much more influence than the difference in terms of instruments or set-up from one lab to another. As expected, luminance matrices measured at the left eye position are roughly the transposes of those measured...
at the right eye position presented in Figure 7.

4.2 Crosstalk ratio

Crosstalk ratios for each eye position have been computed from the luminance matrices according to Equation 7 proposed by Bulat et al.10 The choice of this definition of grey-to-grey crosstalk among other ones has been mainly driven by the fact that it corresponds to a relative luminance error and is easily understandable. Furthermore, other definitions present the inconvenient to have denominators which can be very close to zero when dealing with the whole grey-to-grey combinations and therefore can lead to crosstalk ratios tending to very high values. Again, crosstalk ratios for every combinations of right and left pixels value are presented under the form of matrices. For illustration and clarity purpose, the results in the figures are presented in a logarithmic scale, and values have been cropped between 0.001 and 3 (logarithmic values between -3 and 0.48), since for low grey levels in the measured view and high grey level in the other view, crosstalk ratios can be up to 10 (100%). This is not surprising since in that case the reference luminance is very low, furthermore this is in accordance with the results of a previous study.10

Figure 9 presents crosstalk ratios measured at the right-eye position in Lab3 with both measurement methods, and Figure 10 presents crosstalk ratios at the left-eye position obtained from the second measurements method and compared across laboratories and measuring positions on the screen. It can be first observed from these figures that crosstalk ratio is varying with right-left combinations according to a pattern which is hardly predictable. As expected, the highest values are found for low grey levels on the measured view and high grey levels in the other. Apart from that the crosstalk matrices are quite surprising. Variations of crosstalk with right and left pixels values is not monotonic and some “ridges” and “valleys” can be observed. Despite this unpredictable pattern, crosstalk matrices obtained with different conditions are very recognizable.
Figure 10: Crosstalk ratios (logarithmic scale) measured at the left-eye position from the luminance matrices presented in Figure 8.
When comparing both methods, it seems that the main difference comes from the noise present in the luminance matrices obtained with the first measurement. Indeed, it has been observed that the measurements performed through the glasses were a bit more noisy than the measurements performed directly in contact with the display. This can be due to the measurement set-up itself which was more complex and sensitive in the former case. Even if this noise itself is not so important, it can lead to large variation in crosstalk ratio. Another difference between both methods resides in the pattern itself: if the “ridges” and “valleys” can be similarly observed on matrices obtained with both methods, they seem to be not exactly at the same place. This might be due to the conversion to luminance values, since the range of the raw data was significantly different between both methods.

When comparing results obtained with the second method, the similarity of the crosstalk matrices obtained for each position is quite significant between each of the three labs. Furthermore, patterns are very similar for top-left and center positions. This can be explained by the synchronization between the display and the shutter-glasses. As it has been observed in Figure 6, luminance levels reached by display pixels when the shutter-glass is open are quite similar for center and top-left positions, but can be very far from what is expected for the bottom-right position.

4.3 Reproducibility of the results

In order to study the reproducibility of the results between the two measurement methods and from one lab to another, the distribution of the crosstalk matrices have been plotted in Figure 11. Figure 11a compares the distribution of crosstalk obtained from the right glass with the two different measurement methods, for each of the three measuring spots on the screen. Those distributions are quite similar for all conditions, the main difference is that measurements performed at the bottom-right position spread a bit more towards high values. Table 3 presents the maximum and average crosstalk ratios for the same conditions, except that in that case combinations for which the grey level in the measured view was below 50 have been excluded from the crosstalk matrices (this corresponds roughly to combinations for which the luminance in the measured view is below 1 cd/m²) in order to compare a more coherent range of values.

It can be observed that the average values are comparable from one method to the other with a tendency which is observable for both methods: the lowest average crosstalk ratio is obtained in the center, then the values obtained in the top-left position are slightly larger, and finally average values in the bottom-right position are significantly higher. The largest difference of average values between both methods is obtained at the bottom-right position and is quite significant. Nonetheless, the distribution of crosstalk values for this position is quite similar. Globally, the results variability between both methods is not more significant than the results variability due to the position of the measuring spot.

Figure 11b presents the distribution of crosstalk values obtained with the second method, and Table 2 gives the same statistics as before with the same limitations on the matrices. It is clear from these figures that the variability across laboratories is less important than the variability due to the difference of measuring positions, despite of the fact that three different display samples have been used.

4.4 General comments

It is clear from these results that crosstalk ratio in time-sequential stereoscopic LCDs cannot be evaluated with only one measurement condition. The complexity of the variation of crosstalk ratio across the combination of right and left pixels values necessitate to explore crosstalk with a sufficient number of grey-to-grey combinations. The use of 20 × 20 grey levels seems to be a minimum to picture crosstalk patterns with a sufficiently high precision.

When excluding crosstalk measured for the luminance levels in the measured view, the average crosstalk ratio is found around 6% in the center of the screen, slightly larger in the top-left position (except for Lab2) and significantly higher (around 13%) in the bottom-right corner. Moreover, when taking into consideration all the right-to-left combinations, the crosstalk ratios distribution shows that for the some conditions up to 25% of the combinations give luminance errors higher than 15% (in the bottom-right corner particularly).
Figure 11: Comparison of the distributions of crosstalk ratios (values are in percentage). (a) Comparison between both methods for measurements through right glass performed in Lab3. (b) Comparison between laboratories for measurements through the left glass performed with the second method. The red line indicates the median value, the notch indicates the 95% confidence interval, the blue box delimits the 25th and 75th percentiles.
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<tr>
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<td>StDev.</td>
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(a) Left-eye position

<table>
<thead>
<tr>
<th></th>
<th>Top-left</th>
<th>Center</th>
<th>Bottom-right</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Lab1</td>
<td>Lab2</td>
<td>Lab3</td>
</tr>
<tr>
<td>Max</td>
<td>156 %</td>
<td>130 %</td>
<td>36.7 %</td>
</tr>
<tr>
<td>Avg.</td>
<td>8.59 %</td>
<td>6.05 %</td>
<td>7.24 %</td>
</tr>
<tr>
<td>StDev.</td>
<td>9.32 %</td>
<td>7.20 %</td>
<td>6.77 %</td>
</tr>
</tbody>
</table>

(b) Right-eye position

Table 2: Maximum and average crosstalk ratio measured with the second method. These statistics have been computed after having excluded combinations for which the pixels value in the measured view was inferior to 50 (see text).

<table>
<thead>
<tr>
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<th>Top-left</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Method1</td>
<td>Method2</td>
<td>Method1</td>
</tr>
<tr>
<td>Max</td>
<td>83.5 %</td>
<td>37.7 %</td>
<td>50.3 %</td>
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<tr>
<td>Avg.</td>
<td>6.85 %</td>
<td>7.24 %</td>
<td>6.45 %</td>
</tr>
<tr>
<td>StDev.</td>
<td>7.16 %</td>
<td>6.77 %</td>
<td>5.95 %</td>
</tr>
</tbody>
</table>

Table 3: Comparison of maximum and average values of crosstalk ratio for both measurement methods in Lab3. These statistics have been computed after having excluded combinations for which the pixels value in the measured view was inferior to 50 (see text).

5. CONCLUSION

In this paper, crosstalk in time-sequential stereoscopic LCDs with active shutter-glasses has been investigated. Two different measurement methods using high sample-rate luminance instruments have been carried out. The first one consisted in measuring luminance directly through the shutter-glasses, while the second one proposed to use the temporal characterization of shutter-glasses transmittance in order to simulate luminance observed through the shutter-glass from the temporal responses of the display. These measurements have been performed in three different laboratories, with three different samples of the same display model. The whole right-to-left combinations have been tested, at three different measuring spots on the screen.

Results showed that the crosstalk ratio is varying according to a pattern which is hardly predictable. This is mainly due to the failure of the display to reach a correct luminance level within the short frame period when alternating between different right and left pixels values. Furthermore, significant differences have been found between different positions on the screen. This variability is due to the unequal synchronization between shutter-glasses and display for these positions. This non-linear and non-monotonic behaviour does not permit to describe the crosstalk of a display with simple measurements taken into consideration only a few conditions. From the crosstalk matrices which have been measured in this study, a minimum of 20 × 20 grey levels seems to be necessary to picture a precise enough map of the crosstalk variation at one position of the screen.

This measurement campaign also permitted to show results obtained with the simulation method were quite similar and coherent with those obtained with the classical method. This is an important result since the proposed method only requires some close-contact measurements of the display which are usually easier to carry out and less subject to variations. Indeed, crosstalk measurements obtained with this method in three different labs are in very close concordance.
6. ACKNOWLEDGMENTS

This work has been supported by grant 00156702 of the EU European Regional Development Fund, Mellersta Norrland, Sweden, and by grant 001 55148 of Länsstyrelsen Västernorrland, Sweden.

REFERENCES


