Visual fatigue reduction for immersive stereoscopic displays by disparity, content and focus-point adapted blur

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***Abstract*— As stereoscopic devices become widely used (immersion-based working environments, stereoscopically viewed movies, auto-stereoscopic screens, etc), exposure to stereoscopic images can become lengthy, and some eyestrain can set in. We propose a method for reducing eyestrain induced by stereoscopic vision. After reviewing sources of eyestrain linked to stereoscopic vision, we will focus on one of these sources: images with high frequencies contents associated with large disparities. We will put forward an algorithm for removing irritating high frequencies in high disparity zones (i.e. for virtual objects appearing far from the real screen level). We will elaborate on our testing protocol to establish that our processing reduces eyestrain caused by stereoscopic vision, both objectively and subjectively. We will subsequently quantify the positive effects of our algorithm on the relief of eyestrain. As our processing alters the visual quality of the virtual world, we propose a new adaptation of our method to remove this drawback by coupling an eye tracking to our original processing to keep visual quality on the focus point.**

***Index Terms*— eyestrain, stereoscopic vision, high frequencies, wavelet, eye tracking, blur effect**

I. INTRODUCTION

Stereoscopic immersion has a reputation for producing visual fatigue in long exposures. As many visual immersion devices make use of stereoscopy, it appears important to study the so-called visual fatigue in stereoscopic environments. Visual fatigue is a generic expression which comprises a range of reversible symptoms, usually in the form of ocular and visual problems, as well as more commonly found, less specific ones, such as stinging or heavy eyes, misty or double-outlined vision, persistent headaches, dizziness, etc.

In order to make stereo screening possible we endeavor to reproduce binocular vision and we make use of its basic principles, but in the end a number of differences between the real world and the replicated one cannot be eliminated, and these differences are known to generate eyestrain. Sometimes, people have to work longtime in such immersive rooms, we will try to minimize their eyestrain.

In this article we will, more to the point, study visual fatigue caused by high spatial frequencies in the presence of large disparities occurring in stereo screening. We will propose algorithms for reducing this visual fatigue as well as the results of our experiments, in order to demonstrate the effectiveness of our algorithms. At the end, we will propose to couple an eye tracking device to our processing. The goal is to reduce the visual alteration produced by our method by removing its effect on the object of interest.

We will begin by setting out the sources of visual fatigue in relation to high frequencies. We will subsequently put forward the algorithm of our choice for reducing this fatigue and we will end by presenting fatigue test results to verify the effectiveness of our processing techniques and an analysis of our findings.

II. VISUAL COMFORT AND HIGH FREQUENCY CONTENT

Beyond monocular depth cues such as perspective or shading differences etc., stereoscopic rendering [1] consists of directing two slightly different images to each eye. When the horizontal disparity, in other words the difference between the two retinal images in natural vision, denoted by the angular difference $\alpha - \beta$ (Fig. 1) is too high, the images can no longer be fused by the brain and are perceived as double-outlined (diplopia). The Panum's area is known as the zones around the null-disparity zone where stereo images can be fused. One of the cause for eyestrain in stereoscopic rendering is the breakdown between accommodation and convergence that makes it different from natural vision, but there exist other factors. In the remainder of this section, we will show that high frequencies have an influence on visual comfort.

Wöpking carried out a study on visual comfort in relation with the spatial frequencies occurring in a pair of stereoscopic images. Twelve people were presented a pair of stereoscopic images with calibrated spatial frequencies and disparities. They were asked to try to quantify their level of discomfort, ranging from -2 (very irritating) to +2 (imperceptible) [2] . Perrin designed a comfort function which was basically an interpolation from Wöpking's data. It establishes a relationship between comfort $C(d, f)$, horizontal disparities d and spatial frequencies f. As was the case with Wöpking, the level of discomfort is expressed by a value ranging from -2 (very irritating) to +2 (imperceptible). The comfort function based upon the interpolation of the Wöpking's data is shown hereunder (Fig.2) [3].

$$C(d, f) = a(d - d_0 - kf^{k'}) \tag{1}$$

Where $a = -0.010$, $d_0 = 18.9$, $k = 221.1$ and $k' = -0.74$.

Manuscript received December 18, 2010, Accepted for publication September 15, 2011

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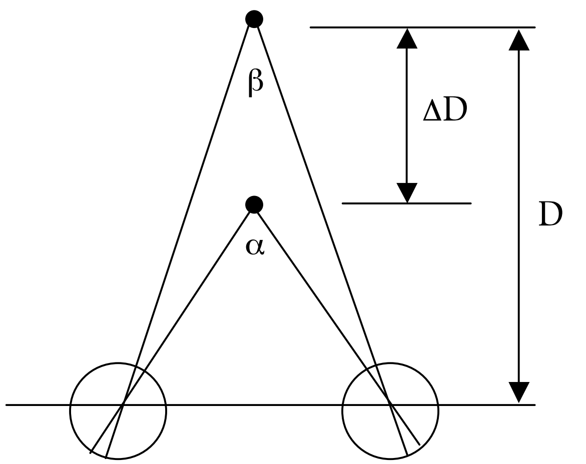

Fig. 1. Retinal disparity

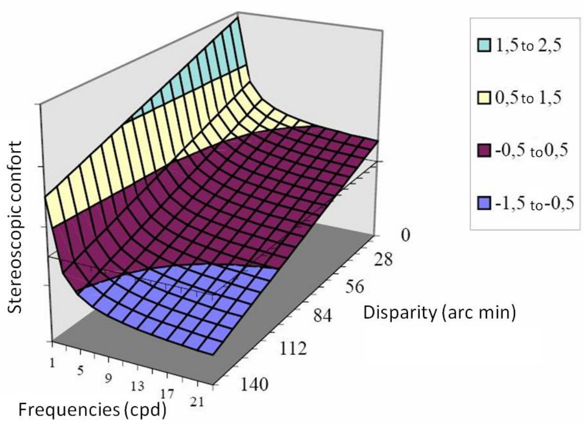

Fig. 2. Perrin's comfort function

III. Related work

In this section, we will give an overview of different techniques that have been proposed to overcome visual fatigue in stereoscopic virtual environments as well as real-time blurring techniques that can be used in those virtual environments. Two types of method have been found: the first ones process still but stereo images while the second ones process dynamic but monoscopic images.

A. Stereoscopic still or precomputed images

Perrin carried out several experiments on reducing visual fatigue, or more to the point, on visual comfort. These experiments were conducted on stereoscopic still images. A virtual tube zigzagged through a virtual world replete with high frequencies and heterogeneous objects. The subject had to slide, along the tube, a ring centered around the tube's axis, without touching it (Fig. 3). This skill test was performed twice, with and without wavelet processing in order to limit high frequencies where large disparities were present. At the end of the tests, the subject had to assess his visual fatigue on a scale ranging from -2 (very irritating) to +2 (imperceptible) [3], [4].

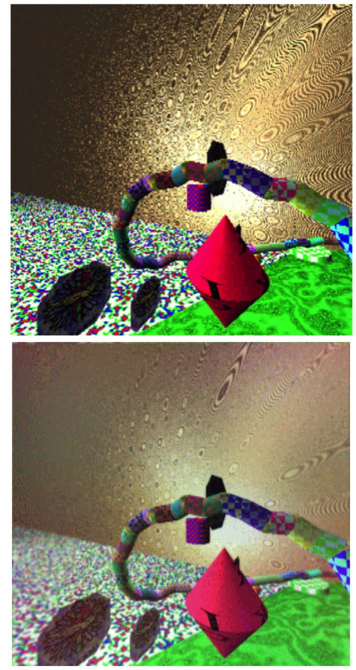

Fig. 3. Perrin's virtual world without and with processing [3]

Wavelet transform computation is however quite heavy on resources. At that time, processing an image could take up to 8 minutes, and that's the reason why Perrin restricted his experiments to stereoscopic still images. Lemmer took over his works and succeeded in somewhat speeding up the process, but he however never achieved real-time computation either [5].

Some studies have created such a depth of field effect for stereoscopic movies with precomputed images. Subjects do not show evidence of a better depth perception, but no results are provided with respect to eyestrain [6].

Blohm [7] and Blum [8] created a depth of field effect on precomputed images (movies) but it was centered on the main object of the scene rather than on the physical screen. They show that it increases visual comfort.

B. Real-time processing of monoscopic images

Hillaire et al [9], [10] studied the use of two kinds of blurring techniques applied to monoscopic images. The first one is a 'depth-of-field' blur which simulates the blurred perception of objects located before or behind the eye's focal point. The second one is the 'peripheral blur' which simulates a blurred perception of objects located in the peripheral sight area. They subsequently studied the influence of such a blur on the way video gamers performed and on their affinities during multi-gamer sessions. They could establish that blurring did not affect the gamer's performance and that moreover the players were in favor of it being used [9]–[11].

IV. Proposition

Since high frequencies, where large disparities occur, are a strain on the vision, we propose to define an algorithm which

TABLE I
SUMMARY OF METHODS

Criteria	Wavelets	Box filter	GPU
	0.5	4.6	97
real time	no	no	yes
decomposition	complete image	complete image	by object
recomposition	complete image	zone	by object
blur type choice	yes	no	yes
link with frequencies	yes	no	no

will locate the higher frequencies prior to removing some of them. This reduction will be related to local disparities, which means that it will be more significant in the large disparity areas. Previous studies have been conducted by means of a wavelet transform [3]. Even though the link with high frequencies is more intuitive, such a process is however too slow to be carried out in real time [5]. Therefore, we have chosen to work on other techniques, such as the one provided by the so-called BoxFilter or other blurring methods [12], [13]. However, our preference went to the blurring method based upon the computing of a sliding average on a computer graphics card (GPU), as it is considerably faster. A brief comparison of the various algorithms is provided in Tab.I.

The GPU method is faster despite its higher complexity because it has the advantage of being completely parallel (pixel-based) whereas the Box filter algorithm is based on the notion of integral image and is therefore totally sequential. So, in order to make a real time processing possible, we have retained as a solution the blur algorithm obtained through computation on a graphics card of a sliding average. From equation (1), we deduce the upper limit frequency for a given comfort level:

$$f = \sqrt[k']{\frac{1}{ak}(ad - ad_0 - C(f,d))} \tag{2}$$

Let us assume that the comfort level must be better than 0. In order to compute a satisfactory frequency by means of equation (1), we want the d-disparity or the horizontal parallax. The latter is obtained by correlating the location of the subject and that of the virtual point. Through the relationships for similar triangles, we can write:

$$HP = \frac{OD * IPD}{ED - OD} \tag{3}$$

Now we know the acceptable upper limit frequency at a given point. However, spatial frequencies are irrelevant to graphics card soft/hardware's, which only take pixels into account. We will therefore have to translate our spatial frequency (in cycle per degree of visual angle) into pixels (Fig.4).

We take the visual half-angle as a basis and we apply trigonometry rules to a right-angled triangle (Fig. 5):

$$tan(\frac{1\,\text{deg}}{2}) = \frac{SD/2}{ED} \tag{4}$$

Therefore

$$SD = 2 * tan(\frac{1\,\text{deg}}{2} * ED) \tag{5}$$

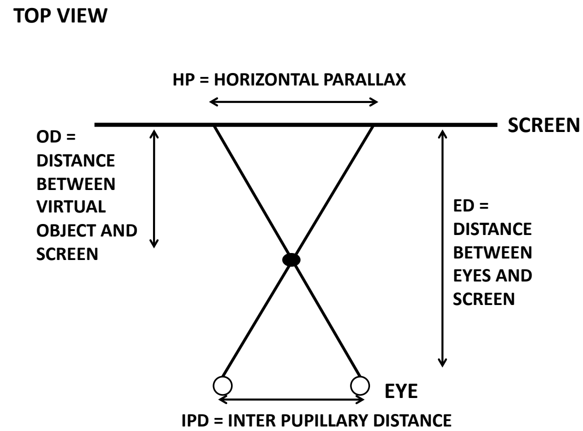

Fig. 4. Horizontal parallax

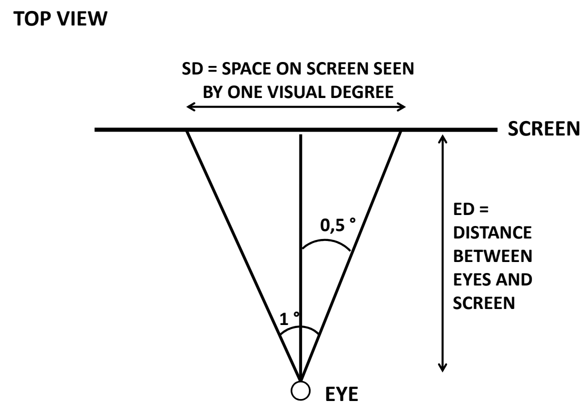

Fig. 5. 1 degree field of view at screen level

And as our pixels are of width N, we can say that the number of pixels per half-degree of field of view equals:

$$NPPDV = \frac{2 * tan\frac{1\,\text{deg}}{2} * ED}{N} \tag{6}$$

The averages will consequently be computed on that number or pixels, divided by the spatial frequency considered for a given disparity. The generated blur is quite progressive, and is a function of disparity.

V. EFFECTIVENESS OF THE PROCESS

To assess the effectiveness of our process, we have to measure visual fatigue. This will be done by experimenting on a set of active observers who will have to perform a task in a virtual work that is hereafter described. The task is repeated twice: one day with our image processing, one day without, in random order.

A. Protocol

Our virtual world is made up of 5 vertical cylinders (10 cm in diameter and 20 cm high) located 80 cm from the ground and physically distributed on both sides of the real screen. The environment also contains a 5 cm sphere located at the end of a 60 cm long tube 'connected to' the WiiMote that more or less represents a hammer. A red square (10 cm) is used to designate the target of the task. The remainder of the virtual environment is composed of a screen background and 3 prisms. All these items (except for the red square) are covered with textures rich in high frequencies (Fig.6).

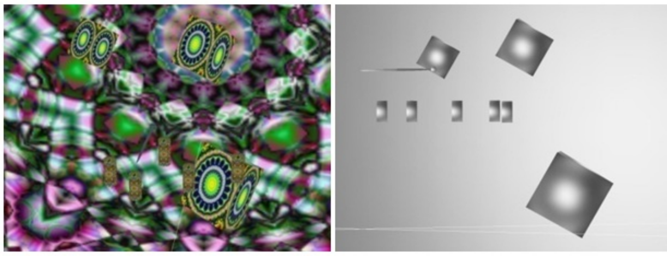

Fig. 6. The experiment virtual world (textured and non textured)

Subjects have to point a randomly designated (by the red square) cylinder with a 'hammer' very precisely 300 times. We measure task effectiveness (positioning error on the cylinders), ease of accommodation before and after (speed of accommodation after moving on to a new target), ponctum maximum of accommodation (this is the minimum focus distance) and stereoscopic acuity (this is the smallest discriminatory perception on the subject's retina) [14].

The subjects selected for the test were aged between 20 and 40. This upper limit was laid down to avoid the influence of presbyopia on accommodation measurements, in particular on ease of accommodation [14]. Visual impairments such as myopia or astigmatism were not considered to be an issue, provided that the subjects were wearing their corrective devices (glasses or lenses). None of the subjects had to cope with stereoscopic adjustment problems, their stereoscopic acuity was better than 63 sec.arc. The results were based on a population of 20, mainly male (85%), individuals. Some of them were accustomed to computer games (40%) but only 10% were used to see stereoscopic images or used to work with them. 75% of the subjects used to work on computers (engineers - 15%, computer scientists - 15%, PhD students - 5%, researchers - 4%), the other subjects didn't use comuters more than one hour a day (nurses - 5%, receptionists - 10%, waitresses - 10%).

B. Physical device

During vision tests (accommodative or stereoscopic acuity), the targets were precisely at a 40 cm distance from the subject's eyes. A music stand mechanically interdependent of a car seat was used to ensure compliance with this prerequisite (left of Fig.7).

The screening surface is provided for by a 3.10 m by 1.74m LUMIN screen. Our projector is a Christie Mirage 3. The screen and the projector's optics are 3.5m apart. Our pixels are 1.61mm wide. The frame per second frequency is 60. The tracking system is a millimeter-accurate ART2 device also operating at a 60Hz frequency (right of Fig. 7).

Fig. 7. Physical setup

1) discussion on display: Many displays were studied to see if some are better for improving the performance of workers in the industry [15], [16]. We, of course, dit not make these fatigue tests on all displays. However, since the calculations depend on the pixel size and spacing of the subject in relation to the screen, we think that the effect produced by this algorithm will produce substantially the same effect on all flat panel displays.

Large displays such as CAVE do not ask a lot of additional calculations: it will calculate the distance between the subject and the screen that is displayed on the object being calculated. Hemi-spherical or cylindrical displays will be slightly more complicated to take into account because of the required image warping (already performed in existing displays).

The principle of the algorithm is not affected by the size or shape of the screen. Limiting high frequencies in areas of large disparities remains valid regardless of the display type.

However, we know that technology (CRT, LCD, projection) affect visual fatigue [17]. It is therefore likely to also impact the effectiveness of our processing. However, as implied fatigues causes are different, we can assume that if this processing works with a technology, it should also end with another.

C. Results

1) Ponctum maximum of accommodation: The measurement method (Donder's Push-up Test) was chosen for its aptness to detect minute variations in visual fatigue [18]. Ponctum maximum of accommodation is measured with a target approaching the eyes of the subject. He tells us when he can reach to read.

Fig. 8 shows the differences in ponctum maximum of accommodation measured before and after each task. It can be seen that the ponctum maximum of accommodation is hardly affected when spatial frequencies are gradually removed by our processing. Without this processing, a loss of 1.21 cm is experienced by the subjects. Their eyes are thus more readily tired when our image processing does not take place. The probability associated with the significance of average differences amounts to 99.6% with the Fisher test which excludes the possibility of a mere statistical aberration.

2) Ease of accommodation: Ease of accommodation is measured by means of a test known as the "Flipper Lens Test". The purpose of this test is to determine the shortest period of time necessary for our eyes to repeatedly adjust to a new stimulus [14]. It is performed with two pairs of lenses (2

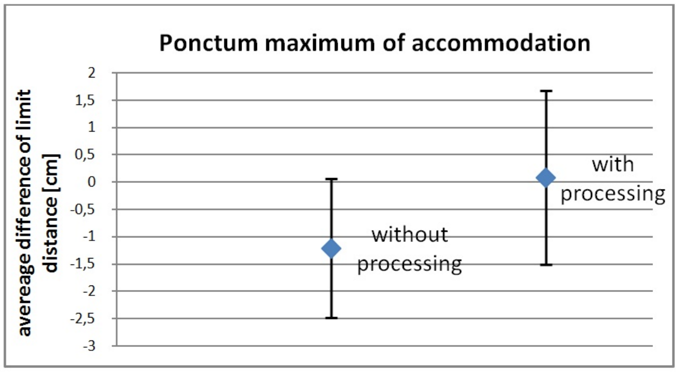

Fig. 8. Ponctum maximum of accommodation modification (negative values show a decrease in performance)

and -2 of dioptrie). We change (half-cycle) the lens when the subject reaches to read the target. Fig. 9 shows the differences in comparative deviations in the numbers of half-cycles before and after the task. The average difference is 1.77 cycles per minute. This is a significant difference, especially since the significance probability associated thereto is 99.45%.

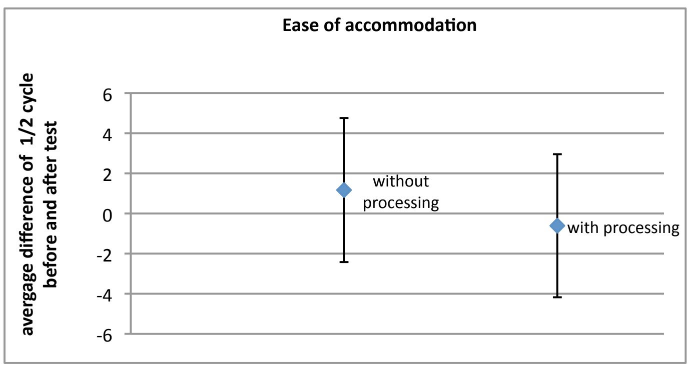

Fig. 9. Ease of accommodation

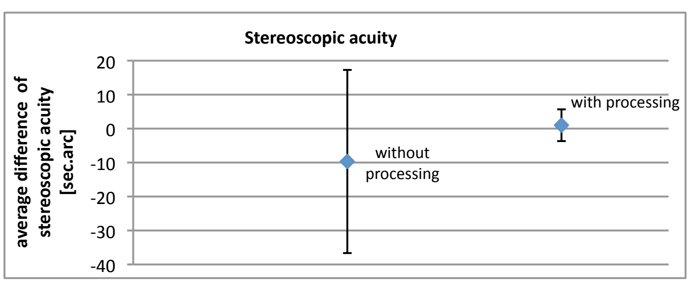

Fig. 10. Stereoscopic acuity

3) Stereoscopic acuity: From Fig. 10, we can see that the difference before and after the test in stereoscopic acuity is quite significant. The stereoscopic acuity appears to be clearly further reduced without our processing and, conversely, it does not seem to be affected when our algorithm alters the image. It should however be noted that this distribution is not normal. The difference between two standard deviations is significant and we have less than 30 subjects. But when we compute the significance by means of these tests, a risk probability less than 0.00001 is observed.

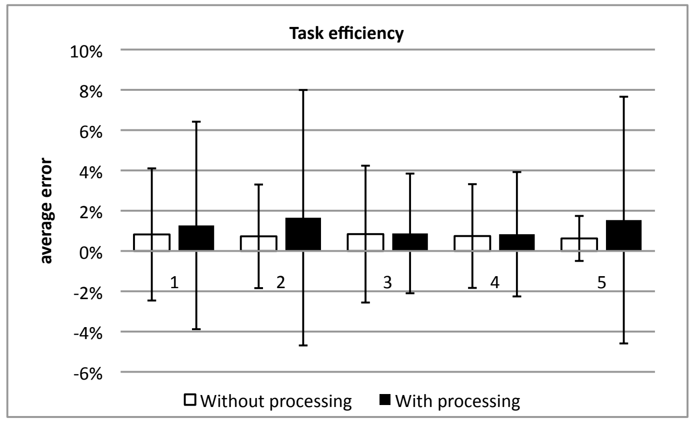

Fig. 11. Task efficiency

4) Effectiveness when the task is performed : Fig.11 shows a chart in which the white bars indicate the average of errors made without processing (expressed in meters) while the black ones represent the averages of errors made with a processing applied, with respect to each of the cylinders. The error bars represent standard deviations. No deviation from the average is however significant, but the differences in standard deviations increase significantly when no processing takes place, except for cylinder 3 which is tied to the screen and for which images are never corrected.

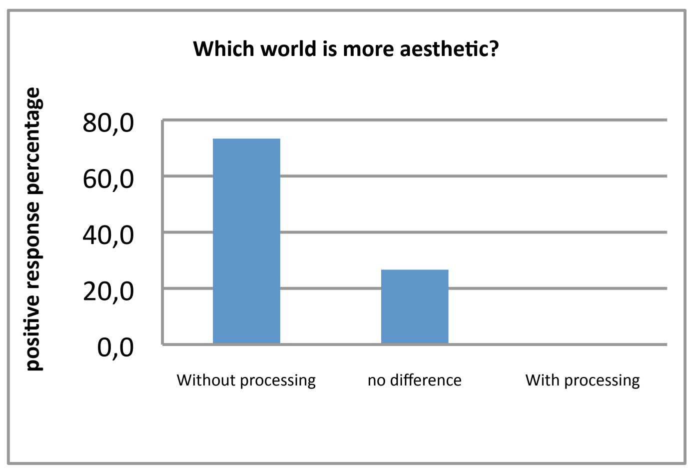

Fig. 12. Which world is more aesthetic?

5) Subjective measures: It can be inferred from Fig.12 that the people subject to the test indicate a preference for a world which has not been cosmetically altered. This does not really come as a surprise since we've intentionally blurred it locally. So our result are in the same way as [6]. It should be further noted that almost one third of the people interviewed did not experience any difference in visual perception from one day to another. Fig. 13 shows that twice as many subjects consider that a world which we did not process is more tiring than the one we did. We can infer from Fig. 14 than the people find the task in the virtual world easier than with processing. This would tend to lend a lot of credibility to the results of the visual fatigue tests we carried out in the previous paragraphs.

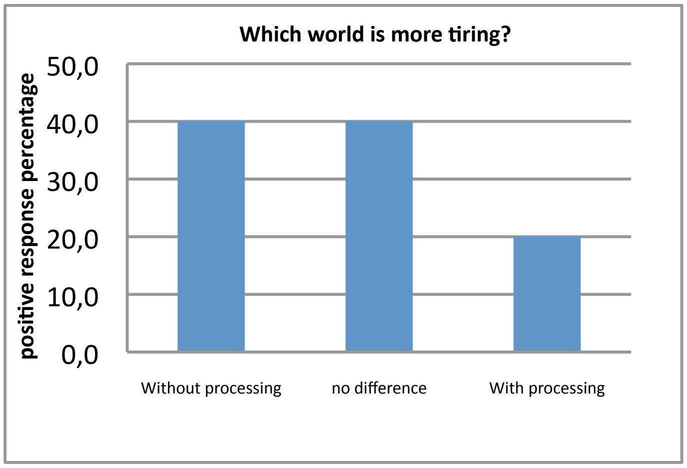

Fig. 13. Which world is more tiring?

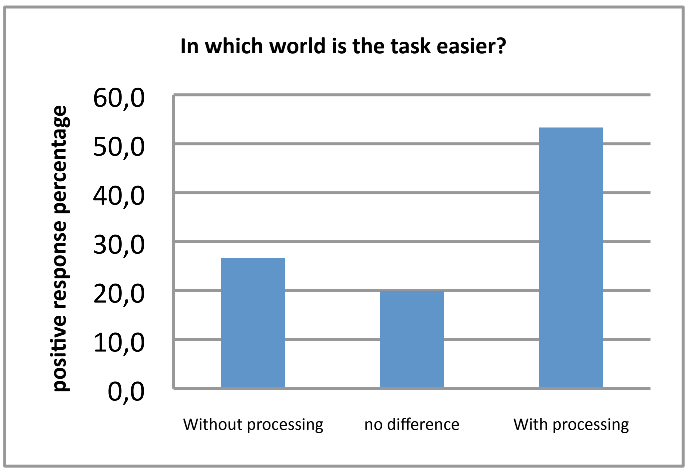

Fig. 14. In which world is the task easier?

VI. Improvements

We have seen that our processing significantly reduces degradation in the ponctum maximum of accommodation as well as the ease of accommodation after immersion. The decrease in stereoscopic acuity following immersion is markedly reduced, or even no longer detected. This tends to prove that our processing truly relieves visual fatigue in immersion, which is confirmed by the subjective questionnaire.

However, we have seen that some subjects perceive that the processed virtual word is less ”aesthetic”. If the application that the subject has to work with requires some geometric or colorimetric accuracy, or any kind of observation of details [19], the processing can be harmful to the task. So, as an analogy with natural vision, we assume that it could be interesting not to process the area on which the subject is focusing. We therefore used an eye tracking system to know precisely the object which is observed and we removed the processing effects on this object. Subjects should not see other objects until they are in the peripheral field of vision.

Studies have shown that a depth of field centered on the observed point in monoscopic vision can improve the immersion of people [9]. So we would like to combine the two processings: a depth of field centered on the screen but which is largely removed on the observed point. We know, thanks to Hillaire, that a such processing can be beneficial for immersion in monoscopic vision [9], so we will try to show that it will be beneficial for immersion in stereoscopic vision.

A. Protocol for preliminary experiment

1) Physical device: The immersive room is the same as for the previous experiment. Though eye tracking device are still an active research field in terms of cost, robustness and speed [20], there exists devices that fulfill our needs: we have used a H6 Head Mounted Optics of Applied Science Laboratories. Its frequency is 60 Hz and the H6 Head Mounted Eye Tracker is designed to track gaze direction over approximately a 30-35 degree vertical visual angle and a 40-45 degree horizontal visual angle. It is connected with the head tracking system, so the subject can stand up and move in the room, exactly in the same condition as in the previous experiment. This device is compatible with active stereoscopic glasses.

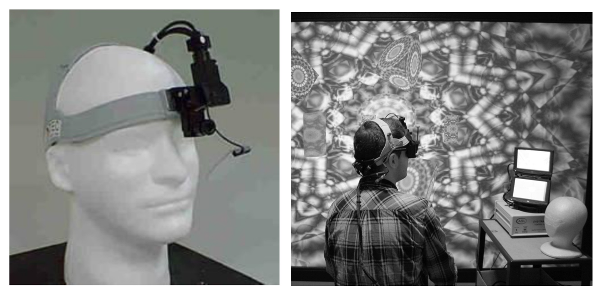

Fig. 15. H6 EyeTracking by ASL [21] and experimental setup

2) Subjects and task: The three subjects are 18 to 40 years old. The upper limit is due to presbyopia, which could disturb the measurement of ponctum maximum of accommodation. 50% of the subjects have already participated in the previous experiment.

The task to achieve in the virtual environment is exactly the same as in the previous experiment.

3) Eyestrain measurements: The eyestrain measurement are performed exactly as in previous tests to avoid biases. They therefore consist in measuring before and after immersion the following variables:

- stereoacuity
- ponctum proximum of accommodation
- ease of accommodation

These measurements are performed under the same lighting conditions and distance as in previous experiments.

4) Blur: As the blur is made on objects, we used a shader that is applied on material. It would be preferable to apply the shader in post-rendering effects, but it was not available on our stereoscopic system. As we have a very small numbers of little objects in the current experiment, we assumed that it is was really an issue to this stage.

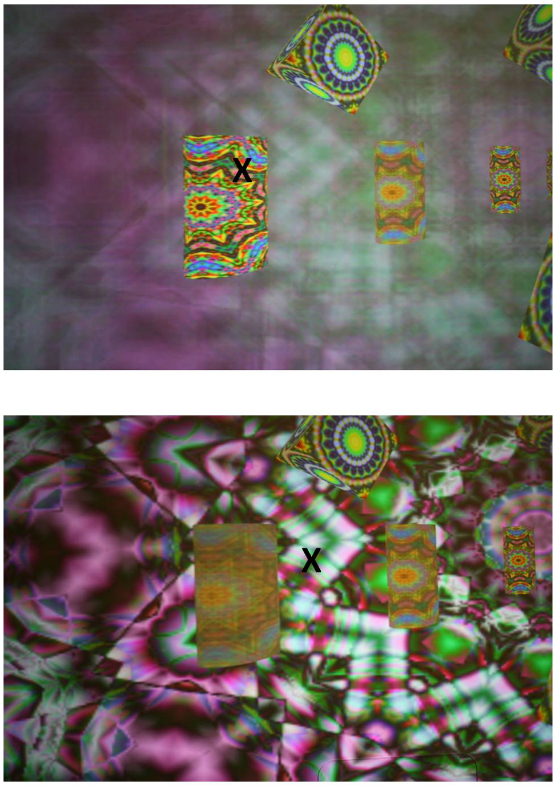

Fig. 16. Blur cancellation on object of interest (denoted by the cross)

B. Preliminary experiment

We do not present quantitative results for reducing eyestrain, indeed, we do have not enough subjects to provide with meaningful results at this time. But on the few subjects who have undertaken the experiment, the decrease seemed similar as for the previous processing. The precision of the pointing task seems good too, even slightly improved. Our approach seems therefore promising. The subjects told us that they did not feel eyestrain with this configuration. However, they had some pain to the neck, because of the weight of the eye-tracking device. As the frequency of natural movements of the eyes is greater than 60Hz, they can perceive the adaptations of the processing, which is a little annoying.

VII. Conclusion

In this paper, we have presented a method for reducing some causes of eye strain in stereoscopic rendering. Our method consists in applying in real-time a blurring effect to zones of high frequency content and high retinal disparity.

We have seen that our processing significantly reduces degradation in the ponctum maximum of accommodation as well as the ease of accommodation after immersion. The decrease in stereoscopic acuity following immersion is markedly reduced, or even no longer detected. This tends to prove that our processing truly relieves visual fatigue in immersion. Furthermore our subjects have experienced a smaller strain while performing the task. On the other hand, the processed images are perceived as less attractive and appeal less to the subjects, even though there seems to be a consensus on them being less vision-straining. This might prove to be an issue whenever aesthetic details play a major role. This should obviously be a point of consideration when dealing with works of art, public exhibitions, and whenever focusing on details is an issue, for example, when inspecting the finish of a manufactured product, etc.

We have proposed a method which allows to perform this processing but that also takes into account the object that the observer focuses on. This new method has to be demonstrated with a significant number of subjects. However, the experiments with the first subjects is promising. We have seen no degradation in task effectiveness. Its precision error remained unaltered. On the other hand, its standard deviation is increased. This could mean that on average the number of errors made by the subjects did not rise, but that compared with an unprocessed virtual world, some of the subjects make more errors and some other less. Furthermore, many subjects claim that processing the image to suppress visual fatigue relieves the strain off the task. In future work, we will make experiments with many subjects to prove that the coupling of the eye tracking system and our method can solve the problem of eye strain without spoiling the virtual world.

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Septembre 15th, 2011