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An Adaptive Blur in Peripheral Vision to Reduce Visual Fatigue in Stereoscopic Vision

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Abstract

For some years, a lot of Stereoscopic 3D contents have been released. Even if the depth sensation is realistic, it is still not perfect and uncomfortable. The objective of our work is to use the gaze of the user to bring closer artificial vision and natural vision to increase the precision of the perception and decrease visual fatigue. For example, a difference in artificial vision is the accommodation point and the convergence point of the eye. In natural vision, these points are the same whereas in artificial vision event if the convergence point is on the looked object, the accommodation point remains on the screen. This difference bring visual fatigue. In this article, we propose and evaluate the effect of an artificial blur in peripheral vision in order to reduce the accommodation vergence conflict and so the strain. We found that adding a blur in peripheral vision decreases the visual fatigue but this blur can't be used actually due to eye-tracker latency.

Introduction

Stereoscopic 3D (3Ds) is now used by a lot of people, even if it is still tiring. For example, in a 3Ds cinema, some people suffer eye strain, headache, dizziness or others factors [17, 3, 7]. These effects have been studied and one cause is a conflict between accommodation and convergence. In natural vision, accommodation and vergence focus on the same object at the same depth. In artificial vision, whereas the accommodation focuses on the screen, the convergence focuses on the virtual object in front of or behind the screen (Figure 1). This difference induces a conflict between the accommodation and the vergence. As the visual system cannot solve this conflict, it brings visual tiredness. Other factor can cause visual fatigue like large disparities, high spatial frequencies or large disparity movements according to Lambooij et al. [3].

To reduce this visual fatigue, we want to improve artificial vision by adding some characteristics present in natural vision but not in artificial vision, such as blurring. In this article, we make a quick review on the techniques already used to reduce the accommodation vergence conflict. Then we explain a new technique using the gaze direction. That technique is to blur peripheral vision in order to decrease the accommodative limits in peripheral vision. We think this technique will decrease visual fatigue because we relax the accommodation constraint when we blur peripheral vision. We have done an experimentation to verify our hypothesis.

Related Work

As we described previously, the accommodation vergence conflict is a cause of eye strain in stereoscopic 3D vision. A lot of people have studied this conflict. Some people created multi-focal system to limits the distance between the convergence point and the accommodation point like Hoffman et al. [4]. They concluded that multi-focal system decrease viewer fatigue and discomfort, increase stereoacuity, reduce time to identify a stereo stimulus and reduce distortion in perceived depth. Neveu et al. [1] showed that beginning with a small conflict and increasing it over the time is better than having a strong conflict immediately.

Wöpking et al. [5] showed that high frequencies induce eye strain. To prove it, the subjects looked at some pictures shown in front of a high frequency background. Perrin at al.[2] extrapolated and plotted Wöpking data to obtain stereoscopic comfort as a function of spatial frequency and disparity (Figure 2). We can see on that graphics that high spatial frequencies are uncomfortable. A solution to that discomfort is to blur the image or some part of the image.

Following Wöpking's and Perrin's results, Leroy applied a blur effect on objects with high disparity to decrease high spatial frequencies [15]. In their experimentation, a cylinder had a red square on it and the subject had to put a sphere on its top for 2 seconds. Then, the red square moved on another cylinder and the subject did it again. The experimentation was in two parts, one without blur and one with blur. To measure the visual fatigue induced by the experimentation, Leroy measured the visual system capacities before and after the experimentation and compared the two results. They showed that adding a blur on object located at high disparities reduces visual fatigue.

Hillaire et al. [10, 12] also increase rendering realism, fun, depth perception and immersion felling when adding a blur effect in a stereoscopic video game, even if they didn't check the influence of their treatment on visual fatigue. They did two experiments, one with the blur centered on the screen and one with the blur centered on the gaze point. They developed a special blur for their experiment which is a mix of three different blurs, a blur using a metaphor to stump the less important objects, a blur for objects depending on their depth and a blur fixed to the border of the screen or in function of gaze point. They concluded that adding their blur effect increase perception of the virtual environment in stereoscopic vision. Users also preferred

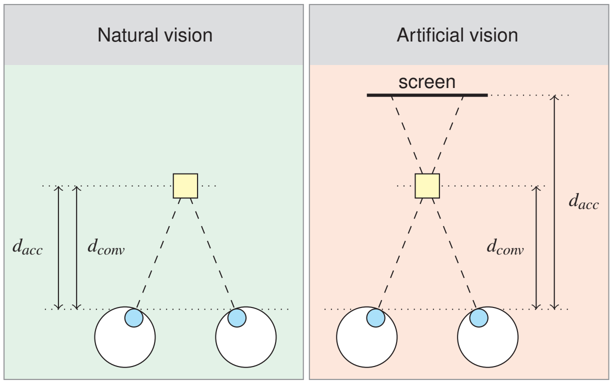

Figure 1. *The accommodation-vergence conflict. In natural vision (left), the distance of accommodation d_{acc} and the distance of convergence d_{conv} are the same. In artificial vision, the two distances are not the same. This difference is the reason of the accommodation vergence conflict.*

when the blur was calculated according to their gaze.

We saw that blurring some part of the images help to reduce visual fatigue and visual comfort. We also saw that the effect of the blur depend on its localization, some use it in high disparities, others on a lot of different localizations at the same time. None of them tried to blur peripheral vision and see the effect on visual tiredness, so we want to check if a blur in peripheral vision can decrease visual fatigue. First, we have to classify different blur and their localization and then, we will experiment the chosen blur in peripheral vision.

Blur localization

High Disparities This kind of blur is applied to high disparities to help merging the left and right picture because the more disparities, the harder it is to merge the two pictures. Leroy et al. [15] applied a blur to objects in high disparities and they reduced visual fatigue.

Based on the gaze depth This blur follow the gaze depth so the objects in the gaze point are always sharp (point F in Figure 3). In front of and behind these objects (point A in Figure 3), objects are blurred. In Figure 3 there is also a gradient of grey, showing the relative depth compared to the depth of the point F. In their experiment, Hillaire et al. [10] used a blur depending on the gaze depth.

Based on peripheral vision The human eye perceives only sharp environment in a 2 degrees cone. This is a consequence of cones density in the retina as the cone density is very high in the fovea and is very low at other location (Figure 4) (Osterberg et al. [8]). The transition between sharp and blur vision is smooth, we cannot notice it. To reproduce this fact, we can add a blur in peripheral vision. A part of the blur used by Hillaire et al. [12] is composed with a peripheral blur.

Transition from blur to sharp In the human vision, we saw that the transition from blur to sharp part is smooth. We present here three equations to model this transition.

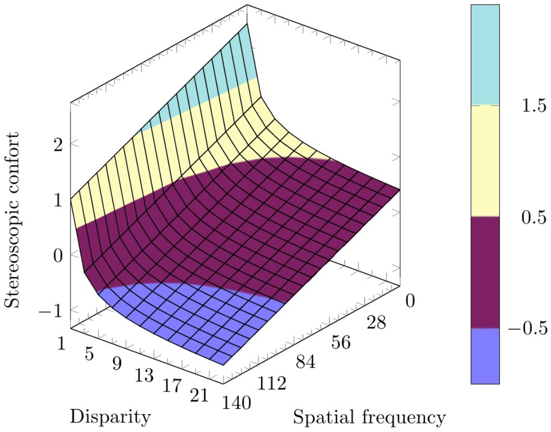

Figure 2. *Stereoscopic comfort depending on disparity and frequency [2].*

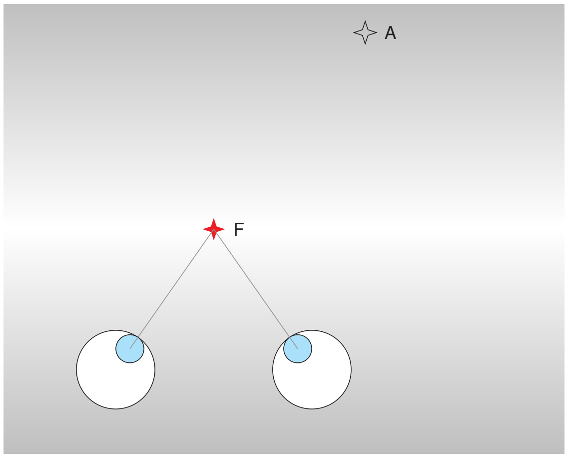

Figure 3. *Depth blur; top view, the two circles represent the eyes. The darker, the far for the* F *point. When the two eyes look at the star (point* F*), the point* A *is blurred because it is further than the* F *point.*

We can do a binary transition (the blue curve on Figure 5), a linear transition (the red curve on Figure 5) or a Gaussian transition (the green curve on Figure 5). The green curve follows the equation (1).

$$Sharp(d) = \begin{cases} 100 \text{ if } d \leq 2 \\ 100 \times e^{-((d-2)\sqrt{ln2})^2} \text{ else} \end{cases} \tag{1}$$

None of the curves are the real one because we didn't find any study about this transition.

Blur computation method

As for the transition, we can compute blur with a lot of different methods. In this paper, we present the wavelet blur and two convolution blurs, one calculated with a mean mask and one with a Gaussian mask.

Wavelets blur The wavelets blur computes frequencies from the picture to remove unwanted frequencies using the

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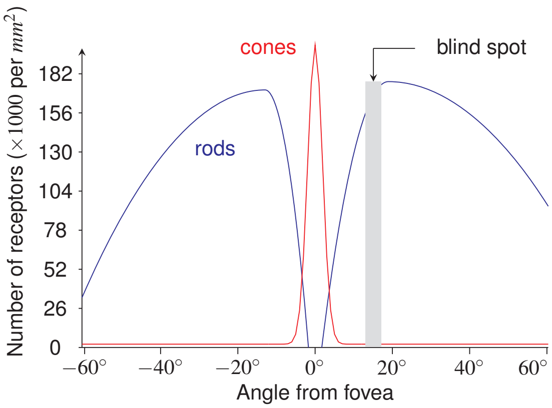

Figure 4. *Density of rods and cones as a function of the angle from the fovea (Image based on the data from Osterberg et al. [8]).*

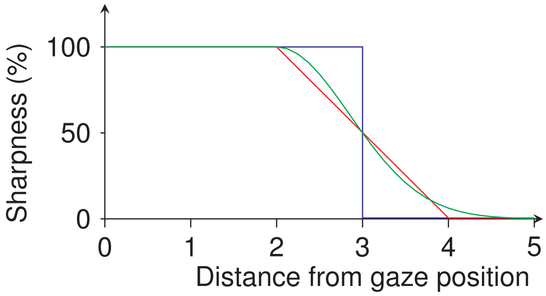

Figure 5. *Transition between blur and sharp area. The blue curve is the representation of a binary transition, the red one is for a linear transition and the green one a Gaussian transition.*

2D wavelet transform like described by Antoine et al. [11]. That method uses 3 steps. First, we have to decompose the picture in sub pictures with different frequencies. Then we delete unwanted frequencies, high frequencies in our case and finally we recompose the picture. Physiologically, that method is the closer one of the treatment made by the brain to compress information according to Campbell et al. [6].

Convolution filter That blur is a mask applied to each pixel of the screen. For a pixel $P(x,y)$ at the position (x,y) on the screen, we can define a rectangle of $(2n+1)\times(2m+1)$ centered on $P(x,y)$. For a pixel on the screen, if (i,j) is the translation between that pixel and the pixel $P(x,y)$ and $p_{i,j}$ is the weight of the current pixel, the formula (2) allows us to compute the new value of the pixel $P(x,y)$.

$$P_{new}(x,y) = \frac{\sum_{i=-n}^{n}\sum_{i=-n}^{n} p_{i,j}\times P(x+i,y+j)}{\sum_{i=-n}^{n}\sum_{i=-n}^{n} p_{i,j}} \qquad (2)$$

Mean mask with unit coefficients We use the formula (3) to compute a mean mask with unit coefficient.

$$\forall(i,j)\in[-n;n]\times[-m;m], p_{i,j}=1 \qquad (3)$$

Leroy et al. [15] used that blur in their experiment. For example, this mask with $n=m=2$ is the following.

$$Mask_{unit}(2,2) = \begin{pmatrix} 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 \end{pmatrix}$$

Mean mask with exponential cofficients The mean mask with exponential coefficients use the coefficients described in equation 4.

$$\forall(i,j)\in[-n;n]\times[-m;m], p_{i,j}=2^{n-|i|}\times 2^{m-|j|} \qquad (4)$$

For example, the mask with $n=m=2$ is the following matrix.

$$Mask_{exp}(2,2) = \begin{pmatrix} 1 & 2 & 4 & 2 & 1 \\ 2 & 4 & 8 & 4 & 2 \\ 4 & 8 & 16 & 8 & 4 \\ 2 & 4 & 8 & 4 & 2 \\ 1 & 2 & 4 & 2 & 1 \end{pmatrix}$$

Rokita [9] used a mask similar to this one to compute faster blur on objects. In equation (4), if we set n and m to 1 and apply the formula, our mask will be:

$$Mask_{exp}(1,1) = \begin{pmatrix} 1 & 2 & 1 \\ 2 & 4 & 2 \\ 1 & 2 & 1 \end{pmatrix}$$

Rotika has the same formula except that the middle coefficient was superior or equal to 4 instead of equal to 4. They used this blur to compute very quickly a blur on objects, but they have not compared it with other blurs or tried to reduce visual fatigue using it.

Mask size In equation (2), the mask size was a rectangle of $n\times m$ pixels. There are some methods to calculate it. The most used is the one introduced by Potmesil et al. [16]. They simulated the crystalline lens using a lens model and they found that the size of the mask (they called it circle of confusion) can be computed using the equation (5).

$$DCOC_d = \frac{D\times f\times(f_d - z)}{f_d\times(z-f)} \qquad (5)$$

In this equation, D is the lens diameter, f the lens focal length, f_d the focal distance and z the point depth.

Related work conclusion

We saw that 3Ds tires visual system because of the accommodation vergence conflict. Several methods have been proposed to decrease this fatigue, like blurring objects to remove high spatial frequencies. However, another possible idea is to blur peripheral vision to facilitate the accommodation process. In the remainder of this article, we test the impact of blurring peripheral vision on visual fatigue in stereoscopic 3D displays.

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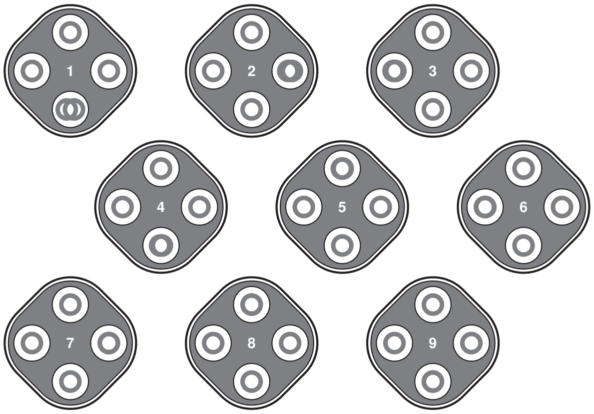

__Figure 6.__ The Wirt test. On the part 1 of the test, the subject see the bottom circle more elevated than the other due to parallax.

Experimental evaluation

Hypothesis

We want to test the effect of a blur in peripheral vision. As the peripheral vision is blurred, the accommodation will focus on the sharp area to process, so it will work less than in case of a totally sharp vision. Our hypothesis is naturally that a blur in peripheral vision will decrease visual fatigue. We are aware that due to low peripheral visual acuity, it is possible that our blur can be useless and have no effect on visual tiredness.

Participants

Eighteen subjects participated in our experimentation, four women and fourteen men (Mean age= 26.2, SD= 3.4). Two subject are not familiar to virtual reality. Some subjects are aware of the general subject of our work. None of them have seen the experimentation before doing it.

Visual fatigue measurement

Lambooij et al. [3] gave a list of visual fatigue measurement. We choose the same visual tests as Leroy et al. [15] in order to compare our results to theirs. We choose to watch stereoscopic acuity with a Wirt test and the variation of accommodation capacity with two tests, the measure of the *punctum proximum* of accommodation and the flipper lens test.

The Wirt test measures stereo acuity from 400” to 20”. In this test the subject looks at four circles and tell which one seem to be more elevated than the others (Figure 6).

In the punctum proximum of accommodation test (PPA) a text is presented to the subject at 40cm from his eyes. When the text is seen sharp, we move the text closer of the subject’s eyes at a constant speed until it is seen blur. Then we measure the distance between the text and the subject’s eyes. The higher the measure is, the more the subject’s eyes are tired.

In the flipper lens test, the subject looks at a text through a lens of -2 dioptres. Once the subject see the text sharp, the measurement begin. We change the lens to 2 dioptres lens and each time the subject see the text sharp, the lens is changed from -2 dioptres to 2 dioptres or from 2 dioptres to -2 dioptres during 30 seconds. We count how many times we change the lens during the 30 seconds. A high value means a good capacity to accommodate, a low value means the visual system is tired.

We also ask subjects seven questions about how they feel before and after the experimentation to evaluate their fatigue. Subjects have to answer with a 6-point Likert scale. Questions are listed as following in the order they were asked:

1. Do you feel your eyes tired?
2. Are you tired?
3. Do your eyes itch?
4. Does your neck hurt?
5. Do you feel heavy eyelids?
6. Do you have tears in your eyes?

Experimental setup

The experiment takes place in our immersive room. The subject is sat on a chair at 2.4 m from the screen and he is centered in front of the screen. The eye-tracker used is a Tobii Rex Developper Desktop Edition. The eye-tracker is 40 cm in front of the subject. The screen is a wide screen (3.1m x 1.74m). We use a F85 projector of ProjectionDesign with a FullHD resolution (1920x1080@120Hz).

Eye-tracker latency

We experiment a blur effect in peripheral vision, the gaze point on the screen is known thanks to an eye-tracker. The latency of our system is an important characteristic of our experimentation. If the latency is too long, the subject can see a blurred image instead of a sharp one, inducing eye strain and decrease visual comfort. It can also draw attention to the sharp area according to Kosara et al. and Huynh et al. [13, 14] which is an unwanted effect.

We have to measure the latency time of our system to be sure these effect will not appear.

Latency measurement The latency is the sum of the eye-tracker latency and the blur computing time. First, we measure the eye-tracker latency. We call eye-tracker latency the time between the subject move his eye and the time to change the rendering. The main advantage of this definition is the inclusion of every latency like eye-tracker internal latency, communication from eye-tracker to computer, rendering time, projector latency. To measure that latency, we film both the subject’s eyes and a feedback on the screen (a point or a cross) with a high speed camera (Figure 7). The camera is a GoPro Hero 3 Black Edition recording at 120 frames per second.

We ask the subject to look at one point, then another and so on to have a lot of eye movement captured. Then, we look at the movie and count the number of frames between the eye movement and the point movement. As we know the frame rate of the camera, we can compute the eye-tracker latency.

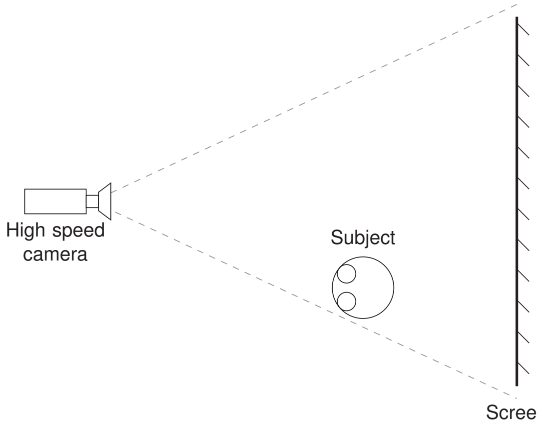

Figure 7. *The latency measurement. The high frequency camera captures the eye and a visual feedback on the screen. When the subject moves his eyes, the feedback also moves after a while. This latency can be computed with the camera movie as we know the frequency of the camera.*

The number of frames computed per second depending on the type of blur and the transition.

		Transition	
		Linear	Exponential
Coefficients	Mean	62	38
	Gaussian	12	7.6

We measured the latency to our eye-tracker (Tobii Rex Developper Edition, Desktop version) and found a mean latency of 150ms.

For the blur computing latency, we have three blurs and two transitions to test. Leroy et al. [15] tried to apply a wavelet blur on pictures, but the computation time was too high to have a real time experiment; the main cause was the implementation of the algorithm on the processor and the fact that the image have to go from the graphic card to the processor. A solution could be to implement the algorithm directly on the graphic card. We choose to use a shader to include the blurring part into the rendering pipeline. So, we have to compare two blurs and two transitions, so four conditions, a mean blur with a linear transition, a mean blur with a Gaussian transition, a Gaussian blur with a linear transition and a Gaussian blur with a Gaussian transition. To compare these blurs, we applied them on a picture and compare their frame rates. The results of this benchmark are in Table 1.

The results show that a mean blur with a linear transition is the faster to compute. We choose this configuration - linear transition and mean blur - to minimize the latency of our system.

Limit of the latency In the experimentation, the screen can be divided into two parts, the sharp area and the non sharp area. In Figure 8, the red cross representing the subject gaze is located in the middle of the sharp area and the green cross is at the limit between the two areas.

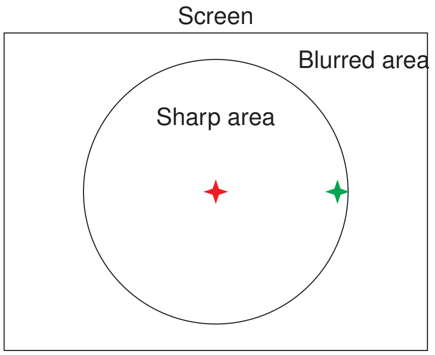

Figure 8. *The limit of the latency.*

If we note R the red point's position, G the green point's position and S the subject's position, the limit of the latency is equal to the time for the gaze to go from the red point to the green point. The maximum angular speed of the eyes $v_{\max}$ is 500 degree per second. The subject is sat at 2.4m of the screen so $RS = 2.4$. In our immersive room, a pixel has a size of 1.6mm per 1.6mm, so the limit of the latency can be computed with the equation 6.

$$T_{max} = \frac{\arctan\frac{1.6\times RG}{1000\times RS}}{v_{\max}} = \frac{\arctan\frac{RG}{1500}}{500} \qquad (6)$$

In the worst case, the radius of the sharp area will be half the width of screen. In that case, $RG = 960$ so $T_{max} = 65ms$. As the eye-tracker latency is about $150ms$, we can see the latency can have an effect on the result.

Task description

Before the task, we measure the visual fatigue of the subject. Then the task begin and when it is finished, we measure again the visual fatigue.

During 30 minutes, the subject looks at a virtual scene composed of ten immobile cylinders and two moving balls in front of a background (Figure 9). All objects are covered with high frequency textures. If the subject sees one ball colliding with a cylinder, he has to click to indicate he saw the collision. When he clicks, both balls disappear and they reappear some seconds after in another place.

The subject is asked to not focus on the two balls and to try to not move his head. The first asking is to not concentrate the subject on the balls and the second one is because the eye-tracker can lose the eye position if the subject moves his head too much. Due to latency we make the balls to move slightly inside a limited area to avoid large gaze movements on screen. This limitations of large gaze movements implies a larger tolerance to the system latency.

There are three conditions, one without blur, one with a large sharp area centered on gaze point and one with a small sharp area also centered on gaze point. Each part take place in a different day so the visual fatigue created by a part does not influence on another one. Even if this influence has not been proved, we want to be sure it won't introduce a bias in our experiment. In Figure 10, we see the sharpness of the rendered image depending on the distance between each pixel and the gaze point on the screen

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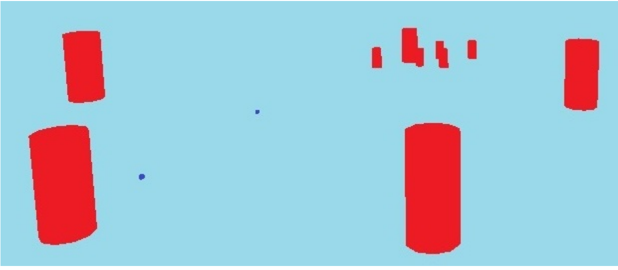
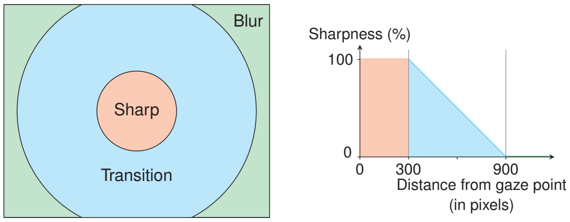
(a) The virtual scene.



(b) The same scene without textures. The colors are light blue for the background, dark blue for the balls and red for the cylinders.

Figure 9. *The virtual scene the subject is looking at.*

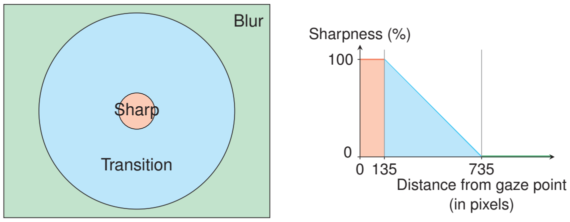


(a) The different areas in the screen. The gaze point is on the center of the screen. (b) The power of blur depending on the distance of the pixel to the gaze point.

Figure 10. *The different areas seen by the subject in case of a large sharp area.*

for the part with a large sharp area. In Figure 11, we have the same graphics for the part with a small sharp area.

The radiuses are chosen to fit eyes acuity or eye-tracker latency. We have seen the visual acuity is very good in a cone with a 10° aperture [8]. The intersection between this cone and the screen is a circle with a diameter of about 135 pixels. That's why the diameter of the sharp area in the condition with the small sharp area is 135 pixels. For the radius of the transition, we choose to include the top density of rods into the transition area. Rods density decrease after an excentricity of about 20°. We choose to separate the transition area and the blurred area at 25 degree to pass through that top density.
For the large sharp area condition, we choose to double the radius of the sharp area to allow a higher latency of the eye-tracker. The sharp area radius is 300 pixels. It corresponds to a cone with a 20° aperture.



(a) The different areas in the screen. The gaze point is on the center of the screen. (b) The power of blur depending on the distance of the pixel to the gaze point.

Figure 11. *The different areas seen by the subject in case of small sharp area.*

Results

Among all subject, three did not match a minimal acuity of 100”, we don't take them into account in our statistics. We tested three conditions: the control condition, the condition with a large sharp area and the one with a small sharp area. The results of these conditions are in Figure 12, Figure 13 and Figure 14.

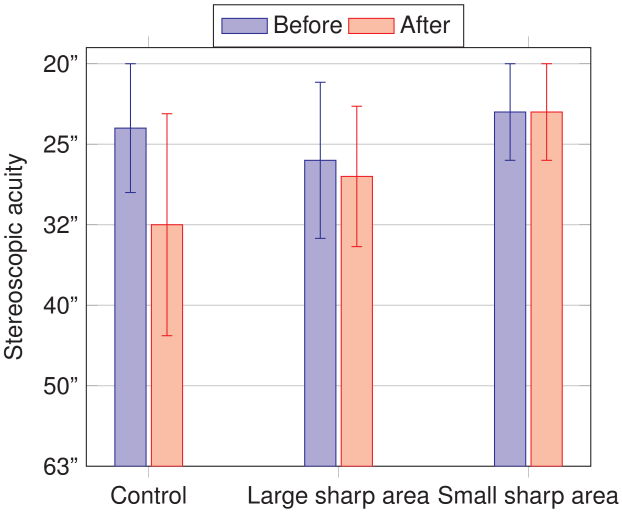


Figure 12. *Results of the Wirt test. A higher score means a better stereoscopic acuity.*

We apply the Kolmogorv-Smirnov test on our population to test if the population is normally distributed and we find that our population does not follow normal distribution (all test were inferior to 60%), so we use a Kruskal-Wallis rank sum test to know if our results are statistically significants. We find a p-value of 0.369 for the Wirt test, 0.464 for the PPA test and 0.484 for the flipper lens test. According to the p-value we cannot conclude about the effect of peripheral blur on visual fatigue.

Some factor can influence the results. The first one is the system latency, as some subject tell us they feel a latency. We measure the eye-tracker latency and we choose the fastest blur, but we must also add the computing time of the OpenGL program. The system latency depends on

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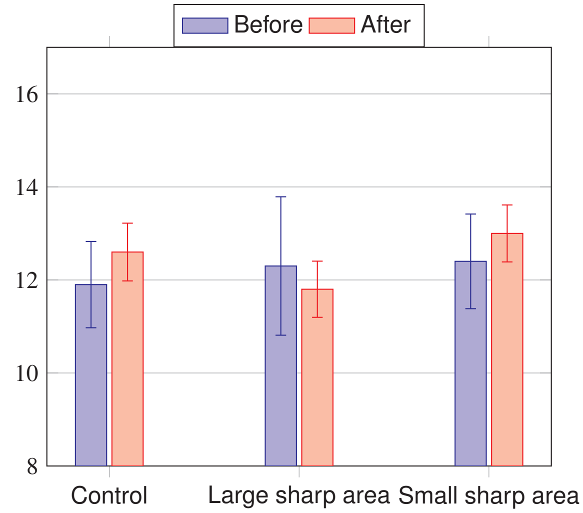

Figure 13. *Results of the PPA test. A high score means the subject have difficulty to accommodate. This difficulty implies visual fatigue.*

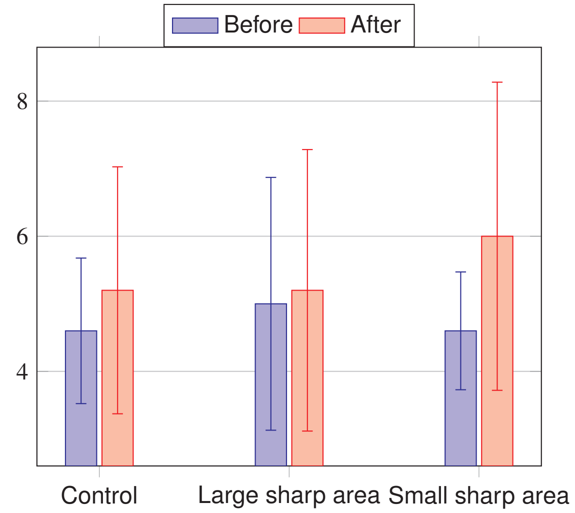

Figure 14. *Results of the flipper lens test. A higher score means more facility to accommodate and so less visual tiredness.*

other factors like CPU load or projector latency (17 ms according to the technical specifications). Because of the important latency, the visual system does not always focus on the sharp area, resulting in unknown effect. It is also possible that a blur in peripheral vision decrease visual fatigue, but the consequences of latency increase it.

Influence of latency

Experimentation and results

To investigate this possibility, we have done a fourth condition. There are some differences between this condition and others. We remove one ball and we set the center of the sharp area on the remaining ball. Then, we ask subjects to look at the ball so the blurred area is always located in peripheral vision and eye tracker latency does not influence the result. We are still using an eye-tracker to verify that the user looks at the ball. If the user looks elsewhere, the computer make a sound to remind the user to look at the ball. Twelve subjects have done this part. We did the same visual fatigue tests - Wirt test, mesurement of the punctum proximum of accommodation and flipper lens test. We compared this condition with a sharp condition. The results are plotted in the histograms Figure 15, Figure 16 and Figure 17.

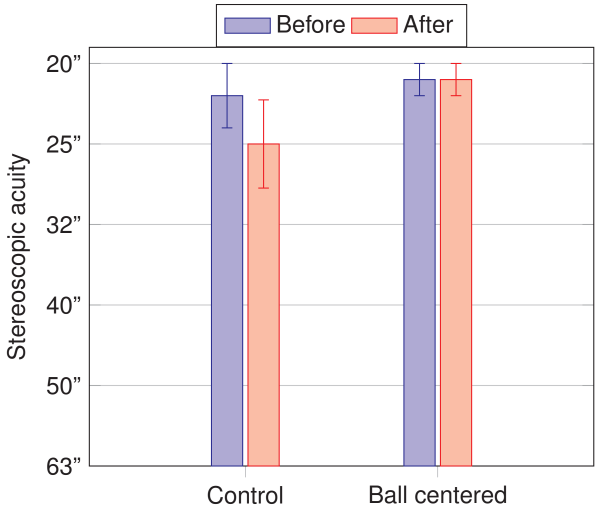

Figure 15. *Results of the Wirt test in the second experimentation to check influence of latency. A higher score means a higher stereoscopic acuity. The eye-tracker was removed in this experimentation to check if it influences on results. Ball centered means the sharp area is centered on the ball.*

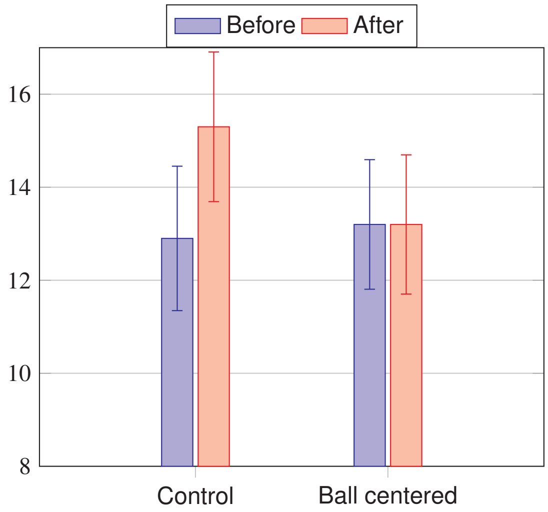

Figure 16. *Results of the PPA test in the second experimentation to check influence of latency. A high score means the subject have difficulty to accommodate. This difficulty implies visual fatigue.*

The PPA test show that the punctum proximum of accommodation get closer of the subject after the blurred condition ($2.16cm$) whereas it get further in the sharp condition by $0.33cm$ (Student test, $p < 10^{-5}$). If we look at the results of the flipper lens test, the subjects do more half turn

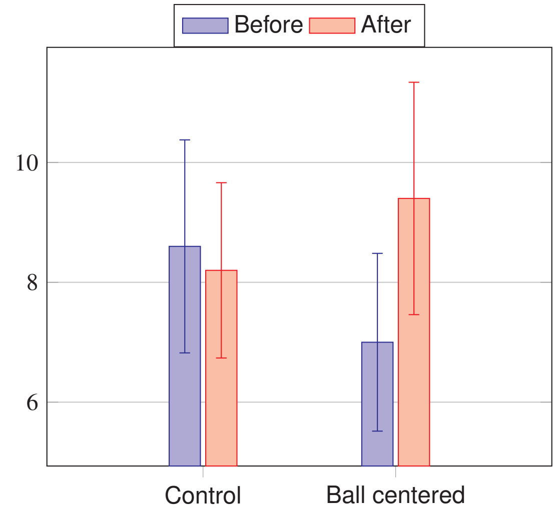

Figure 17. Results of the flipper lens test in the second experimentation to check influence of latency. A higher score means more facility to accommodate and so less visual tiredness.

(2 more half turns on average) after the blurred condition. That two tests show a decrease in visual tiredness when we use a blur in peripheral vision.

We took the mean of the results of the seven questions we asked to have a global feeling of subjects about their fatigue (Figure 18). In this histogram, we see subjects feel tired by the experiment event if there is not a large difference between conditions.

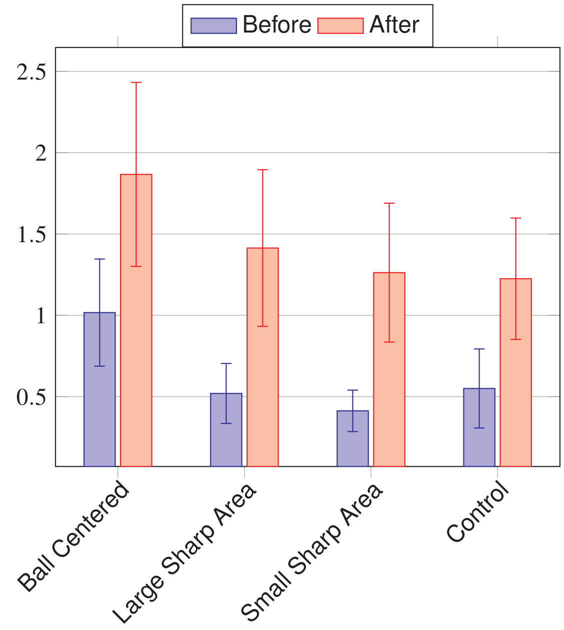

Figure 18. Visual confort felt by subjects in both experimentations. The higher the response is, the unconfortable they feel.

Discussion

Leroy et al. tested a blur depending on disparities and they showed that blur decrease visual fatigue. We know that in artificial vision the accommodation focus on the screen so object are already optically blurred at high disparities. We showed that blurring in peripheral vision also reduce visual tiredness even if it is known that peripheral vision is naturally blurred due to low density of cones out of fovea in retina. These two results show visual strain can be decreased when we improve blurring already present in natural vision. Perhaps other vision characteristics can also help to reduce visual fatigue.
We also saw that latency of eye-trackers can influence that result. Due to latency, eyes try to focus a short moment on a blurred area, which mean more work to focus again on the screen when it become sharp again. With this hypothesis, the relaxation induces by our treatment is minimized by the work to focus on the screen. This can explain our result from the first experiment.
Hillaire et al. applied a blur in depth, in peripheral vision and on objects of less importance, and they increased fun, depth perception, realism and immersion feeling. It seem natural to say something relaxing will be more appreciated than something stressing. So our result could explain Hillaire's one.

Conclusion

We have done an experiment to see if visual fatigue in stereoscopic vision can be reduced using a blur in peripheral vision and found that this technique works.

In a future experiment, we want to investigate another way to bring closer artificial vision and natural vision. Actually, in artificial vision, the directions of the two cameras (one for left eye, one for right eye) are parallels. In natural vision, the two axes of our eyes converge on the object we are looking at. With our eye-tracker, we want to add this convergence to artificial vision. This convergence will induce deformations called vertical parallaxes, and we want to study the effect of vertical parallaxes on distance perception, shape perception and visual fatigue.

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