Visual immersion issues in Virtual Reality: a survey

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***Abstract*—Thanks to immersion and interaction, Virtual Reality (VR) offers a shift of paradigm compared to traditional computer graphics or simulation software. Most VR applications include a visual rendering part. However, efficient and relevant visual interfacing of a human user (who can be a designer, the final user of a future product, a trainee or the subject of an experiment) raises issues about visual interfaces and depth perception in computer generated images. In this survey we review the issues raised by the visual part of VR applications. We particularly focus on the commonly used stereoscopic vision by studying its constraints and show how an efficient stereoscopic application should be designed.**

***Keywords*-Virtual Reality, immersion, interaction, depth perception, stereoscopic viewing, visual fatigue**

I. Introduction

Thanks to immersion and interaction, Virtual Reality (VR) offers a shift of paradigm compared to traditional computer graphics or simulation software. Most VR applications include a visual rendering part. However, efficient and relevant visual interfacing of a human user (who can be a designer, the final user of a future product, a trainee or the subject of an experiment) raises issues about visual interfaces and depth perception in computer generated images. Most of these constraints are unknown to the majority of VR applications developers who generally consider the most *realistic* solution to be the best and therefore stack up all available technology and most advanced rendering techniques they can to their application. This leads to application failure and rejection of VR. One famous VR-related example of stereotype is that ”stereoscopic visualization causes headaches”. When hearing that, it is quite common among the VR community to ask why application designers are using stereo and how stereo parameters are tuned. Answers to those questions are usually ”Because it looks better” and ”Errr...”. These issues become of paramount importance with the development of 3D cinema or 3DTV. One motivation for this survey is to overcome the current preconceived ideas about stereo rendering and more generally about visual interfacing in Virtual Reality.

The term *Virtual Reality* is generally admitted to have been introduced in the field of computer science by Jaron Lanier in the early 1980s (even though Antonin Arthaud coined the term earlier for theater [1]). Numerous definitions can be found in the literature, we will simply stick to define Virtual Reality by its finality as in [2], i.e. to allow one or several people to do sensory-motor, and thus mental, experiments in an artificial world, which is either imaginary, or a simulation of some aspects of the real world. The two main assets of VR are immersion and interaction. Immersion implies the concept of presence whereas interaction ensures the user is actually doing something, i.e. his actions have a real-time influence on the way the interactive world is presented to his senses. Mel Slater insists on place illusion and plausibility as being key factors for realistic user behavior [3]. Obviously interaction favors the feeling of presence. In professional applications, the artificial world in which the user is immersed is usually to some extent the reproduction of elements of our real world with a change of location, time (representing a future product for example) or interaction type with a given *degree of realism*. However, the degree of realism is limited by technical and economic constraints, we will see some of those in the following paragraphs. Virtual reality is theoretically able to address all human senses and motor actions. Yet, it is clear that a wide majority of VR applications include a visual rendering component that will be the focus of this paper.

This survey starts with a brief introduction to the human visual system features that impact VR and its complexity, it then focuses on depth perception in both monoscopic and stereoscopic vision. The following part introduces the available devices to provide visual immersion in Virtual Reality. The last part is dedicated to the specific problem of stereoscopic vision in artificial environments. The creation of stereo images both on the hardware and software part is addressed. The limitations of stereo in desktop screens or large VR facilities are shown, recent research works dealing with improving stereoscopic visualization is presented.

II. Scientific and technical issues of visual interfacing

The objective of this section is to introduce the Human Visual System (HVS) and its influence on visual interfacing and perception in Virtual Reality. We will firstly present the HVS through its main features with respect to Virtual Reality and then switch to the crucial problem of depth perception. We will distinguish between monoscopic depth

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cues (i.e. depth cues that can perceived with only one eye) and stereoscopic depth cues (that are only constructed by stereopsis). In a second time, we will briefly review the available visual interfaces for VR.

A. The Human Visual System

The anatomy of the human eye is presented in Figure 1 for further understanding of some terms. There remains a lot of active research on the HVS but we will focus on a few decisive points as far as VR is concerned: field of view, visual acuity and contrast sensitivity

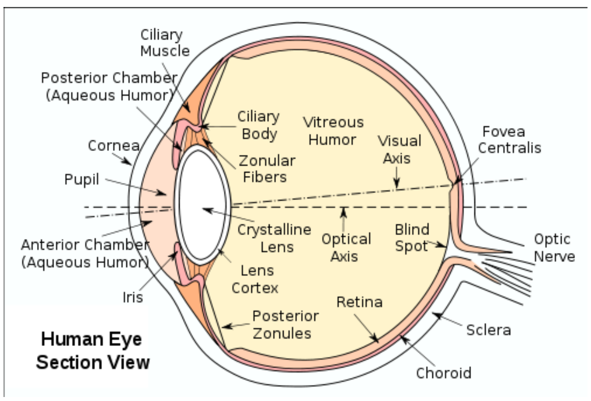
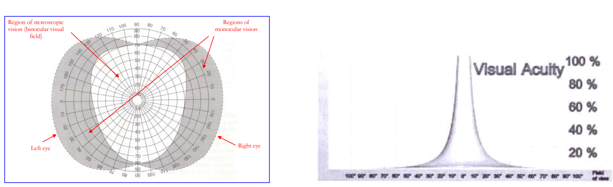


Figure 1. Anatomy of the human eye (source: Wikimedia).

The human field of view has been shown to be of importance in VR as it impacts presence [4] or task performance [5]. The monocular visual field of view is determined by having a subject fix a point in the center of his viewing area (200° H × 135° V according to [5]). Its shape is roughly circular. The areas of visibility that are common between the two monocular fields are named the binocular visual field. Figure 2 (a) shows the human field of view and the overlap between the eyes. When a good visual immersion is sought, the motion of the eyes and of the head must be taken into account. An eye can turn around its orbit by 15° both in the horizontal and vertical direction, with a maximum speed of 600° per second. The head can turn at the speed of 800° per second.



(a) Field of View

(b) Visual acuity

Figure 2. Human visual system important features for VR (from [6])

The ability to resolve fine spatial details is named visual acuity. Visual acuity is not homogeneous throughout the field of view, it is influenced by eccentricity. For a normal eye it reaches its maximum in a two-degree centered cone. The minimum angle value under which two points are distinguished depends on the observed stimulus:

- A lit line on a dark background: $30sec$ angle (i.e. $0.5 \times 1/60°$)
- Two bright dots on a dark background: $1min$ angle (i.e. $1 \times 1/60°$)
- Two dark dots on a bright background: $2min$ angle

Figure 2 (b) shows visual acuity with respect to the field of view. Taking into account the fact that current eye trackers are technically not able to follow in real-time the direction of sight with very sufficiently low latency and thus to have adaptive display resolution with respect to the focus point, we are forced to use interfaces that ideally would reach human visual acuity in the whole field of view. It must also be said that visual acuity is influenced by contrast (and thus by luminance) and by object speed.

While visual acuity has been one of the time-honored descriptors of human spatial ability, it only provides information about the extreme upper limit of the spatial dimension to which we are sensitive. Much of what we see and use may not involve spatial details near these limits. A popular approach to evaluate human sensitivity for objects of different sizes has been to specify the contrast necessary to detect them. In the simplest case (a light bar on a dark background) contrast C can be defined as $C = \frac{\Delta L}{L}$, where L is the background luminance and ΔL is luminance increment (or decrement) provided by the bar. It is important in VR as video-projectors for instance have a fairly limited luminance range with respect to natural lighting.

B. Depth perception

This section is dedicated to depth perception in both monoscopic and stereoscopic viewing. Monoscopic cues are implicitly included in off-the-shelf rendering engines. The most prominent one is perspective (centered projection). Other static monoscopic cues include luminosity variation between faces of an object due to Lambert's law, relative dimensions of objects (a consequence of projection), inter-object occlusion (included in Z-buffer-like algorithms), texture variation (another consequence of projection and Shannon's theorem) or visibility variation in outdoor scenes. There also exists kinetic cues such as motion parallax which can be obtained with object or observer's motion. At last, proprioceptive cues using accommodation and vergence variation can be added, they will be discussed later on.

Stereoscopic vision was first explained in 1838 by Wheatstone [7]. Although most people view the world through two eyes, we usually see a single unified view of the world. The brain receives two different images that are fused into one representation in what is called the stereopsis process. A point in space might thus be differently located among the two retinal images of the left and right eye. For example, if the eyes are focusing (converging) on a point F in space, any other point A in space will have what is called a retinal disparity, defined as $d = \alpha - \beta$ (see in Fig. 3). Retinal disparity is used by the HVS to evaluate depth: the *horopter* is the theoretical line of all points with no disparity. But fusion between two images is limited around the focus point, Panum's area is the set of points around the horopter that can be fused. Points outside this area will be perceived as double points. Experimentally, it has been shown that fusion should be roughly limited to $|d| \leq 1.5°$ to allow stereopsis [8]. Julesz [9] has shown that binocular cues are enough to perceive depth in the total absence of monocular cues. Note that the proposed figures are approximates as Panum's area is not symmetric, has inter-individual variability and also temporal and dynamic dependency (fusion limits are different with respect to exposure time and depend on the speed of disparity evolution).

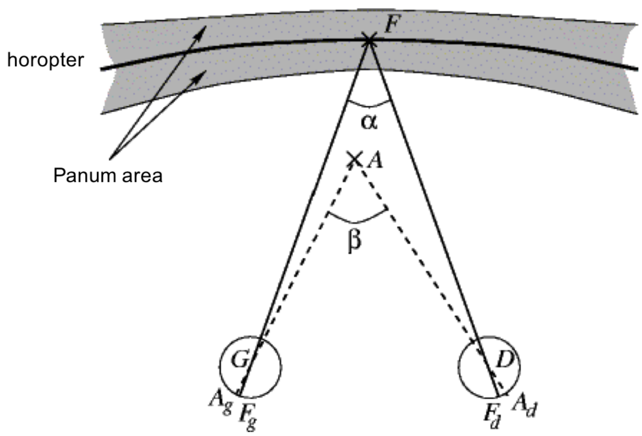


Figure 3. Retinal disparity and Panum's area

The last important point for depth perception is linked to the fact that in real vision, the eyes converge and accommodate on the same objects. The brain retroactively acts on the eyes: first by commanding the muscles that rotate the eyes for convergence, and second by commanding muscles that deform the curvature of the lens for accommodation (the distance at which we look). With the help of muscles, the power of the lens can vary and thus enable focusing on the retina to be able to see close or far objects: it is the accommodation phenomenon. The crystalline lens is the only diopter of the visual chain which power can vary. Every light ray is directed toward the fovea that is the central point of the retina. The accommodation level is set to obtain a good image.

With binocular viewing, the two eyes converge when viewing near objects and diverge when viewing objects further away. The muscles of the orbital globes allow to rotate the two eyes and to make them converge on the observed point. It is the convergence phenomenon. As accommodation, convergence occurs automatically and unconsciously.

In VR, the eyes accommodate on the screen whereas the eyes still converge on the object of interest as shown in Figure 4. This breakdown between accommodation and convergence is one of the cause for people being said *not being able to see in stereo*. The breakdown must also be limited to allow stereopsis [10].

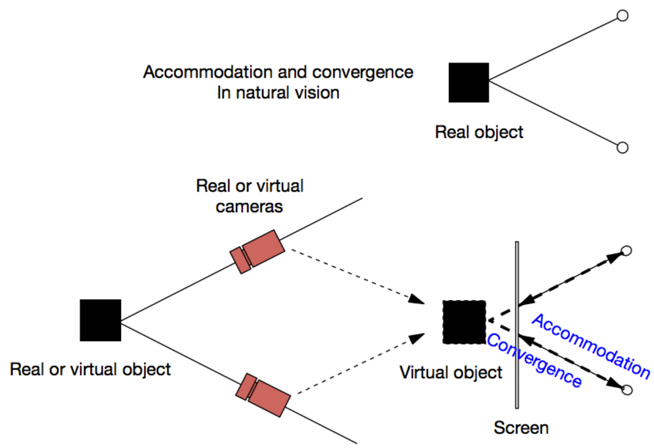


Figure 4. Breakdown between accommodation and convergence

Last but not least, in natural vision, defocus blur occurs for objects that are not within a distance of the focus zone which helps *forgetting* those objects and not trying to fuse them. We will see that the absence of defocus blur in traditional OpenGL-like real-time computer generated images can modify our perception [11] and be a source of eye strain.

C. Visual interfaces for VR

The use of visual stimuli is almost always necessary in virtual reality. Therefore, visual interfaces have been developed over the years more than any other interfaces. The ideal visual interface should have metrological characteristics similar to the ones of the human eye. This implies four greater features than the ones of an ordinary desktop screen: large horizontal and vertical fields of view matching the ones of the eyes, stereoscopic vision in the whole visual field, high resolution up to human eye visual acuity and complete sight immersion. This last issue is only addressable thanks to the use of head motion tracking system. Of course, computer power is also required in order to generate the images for both eyes. At this point, we can say that technically two different kinds of immersion are proposed:

- Total sight immersion in an HMD or in a six-faced immersive cube. The head of the observer can translate and rotate in any direction.
- Partial and concentric immersion of sight: in front of a screen (as large as possible), the observer can translate and rotate his head with limited distance and angle.

A few examples of visual interfaces are given in Figure 5. Two main types can be distinguished:

- Fixed interfaces which range from the basic monoscopic desktop display to the 6-face CAVE-like device [12]. Screen(s) can be either planar or curved such as in so-called immersive room. The bigger the displays, the more expensive and the less reconfigurable and/or moveable the system. Immersion is clearly linked to the field of view [4] which explains that CAVE can be perceived as better tools for immersion than desktop monitors. As far as stereo is concerned, it has been shown that tracking the observer's head is more important for shape perception [13].
- Mobile interfaces such as Head-Mounted Displays (HMD) whose goal is to provide the observer with two small screens (or a single screen and appropriate mirrors to divide images) placed in front of the eyes in order to obtain stereoscopic vision together with a large field of view and sight immersion. Yet, HMDs face a contradiction between the necessary miniaturization of the screens and the desired large field of view. screens are thus very close to the eyes and require complex and costly optical systems, which might be an explanation for the lack of success of HMDs for the last thirty years. HMDs also face ergonomic issues [14] potentially including low-quality images, heavy weight, a *pigtail effect* slowing user's motion due the important number of cables and challenging issues such as an easy and repeatable positioning of the HMD and its screens with respect to the user's eyes.

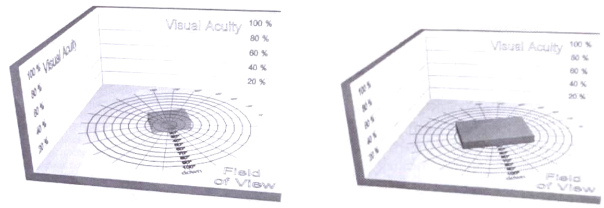
(a) Barco Baron workbench (b) SASCube Clarté (c) NVision Datavisor 80

Figure 5. A few VR visual interfaces

In the end, it must be reminded, as shown in Figure 6 and in [6] that current VR visual interfaces are far from reaching the ideal conditions mentioned at the beginning of this section.

III. Stereo images

Although the principles for the creation of stereoscopic images have been known and used for a very long time [7], [15], those principles remain unknown to most people working in Virtual Reality. For most applications developers, stereoscopic rendering is limited to a couple of static parameters that are usually tuned without further knowledge.



(a) PMD 80 HMD (b) Move CAVE

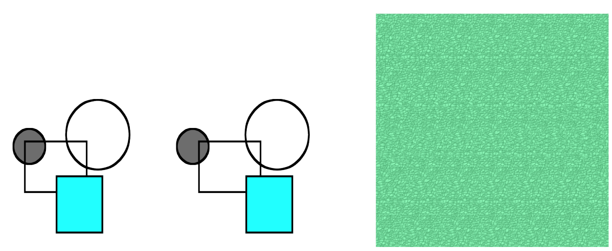
Figure 6. Limitations of current visual interfaces with respect to field of view and visual acuity [6].

We will thus focus on the technical means to provide one or several users with stereoscopic images and will give a short insight on how to efficiently give stereoscopic capabilities to VR applications. We will present some recent works on the effects of stereoscopic images and on reducing visual fatigue during long stereoscopic immersive sessions.

A. Hardware for stereo images

In this section, we will briefly introduce the two main ways of producing stereo images which consists in generating two slightly different images and displaying one to each eye. Basically, images can be separated at eye level (the most intuitive way) or at screen level.

Separation at eye level can be done without any hardware. For example, if a person manages to stare at the images presented in Figure 7, he/she can build a 3D image. Yet, this is not easy to achieve, this is one of the reason other devices were built. HMDs belong to this category.



(a) Direct eye separation (b) Stereogram

Figure 7. Stereo images with no hardware

The other method to present stereo images to an observer is to separate them at screen level. This can be done in two different ways:

- Video-projectors: they are used to project two different images (one for each eye) that are filtered with specific glasses so that each eye can see only one of those images. If glasses with LCD-shutters synchronized with projector are used, it is called active stereo. Conversely, if two different projectors are used along with polarizing filters, passive stereo is performed. The glasses will be simpler in that case, they are only polarizing glasses.
- On the other hand, auto-stereoscopic screens do not require special glasses. They usually use an array of

vertically disposed micro-lenses such that for example odd pixels are only visible for the left eye whereas even pixels would only be visible for the right one (see principle in Fig. 8). Although the process dates back to the end of the 19th century, the first complete rendering and acquisition system was put on the market in 1987 [16]. Auto-stereoscopic screens face lag issues (vertical line interleave between left and right image is not easy in GPGPU) and require adequate placement and orientation of the observers which limits immersion capabilities (large field of view or multi-screen are hard to achieve). But they are now becoming widespread (Nintendo 3DS) and can be extended to many more simultaneous users.

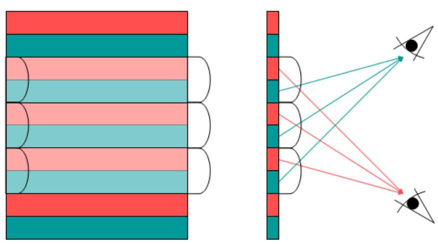


Figure 8. Principle of lenticular lens: depending on the angle vision, either the red or green image can be seen. (quoted from Wikipedia)

B. *Creating stereo images: the software side*

In this section, we will provide rules for creating Virtual Reality applications that create consistent and correct stereo images. Most VR developers see stereo as activating a specific mode in a software and setting up two parameters, the *inter-pupillar distance* (*ipd*) and the *angle of convergence*. According to section II-A, these parameters are not fixed. We will also elaborate on the limitations first shown in II-B and will provide a set of rules for setting up stereo parameters based on the ones used in [8].

At first, we have seen that for projection on screens, convergence can be kept whereas accommodation is fixed as the distance between the eyes and the screen. As far as convergence is concerned, we could ask whether we should use converging virtual cameras such as represented in Figure 9. Intuitively we would like to have them move and converge as the human eyes do in real time. Unfortunately, not only it is very difficult to track the eye fast enough but it also creates vertical parallax (i.e. vertical shifts between homologous points in the two images) which is far more difficult to bear than horizontal parallax and can cause severe eyestrain [17].

If eye tracking is difficult to achieve, head tracking of the observer remains of paramount importance: [13] reminded in that head tracking was providing more benefits than stereo. Combining both can have complementary benefits but the lack of tracking has consequences on shape perception as it distorts objects. This phenomenon, shown in Figure 10, for lateral motion is called pseudoscopic motion.

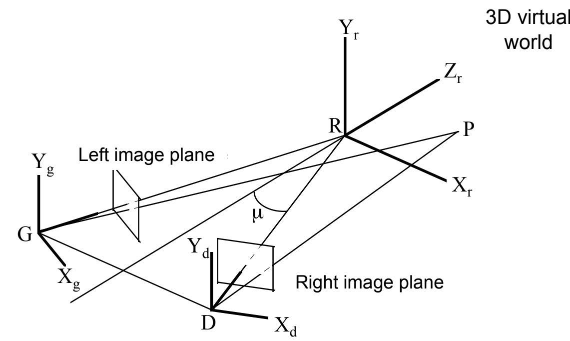


Figure 9. Convergent virtual cameras

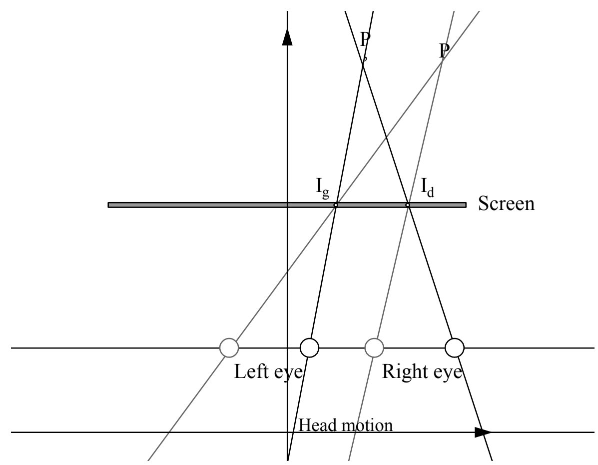


Figure 10. Pseudoscopic motion when the observer moves his head to the right without head motion tracking.

The following are a briefly commented set of rules:

- **(A)** The accommodation-convergence relation must be only slightly modified [10]: the main object should have a low (ideally null) parallax;
- **(B)** Image fusion should be possible and easy, implying low eyestrain
  - (B1) Horizontal parallax should be limited but high enough to perceive depth. Limits for horizontal and vertical parallaxes are generally the same for positive and negative values (1.2° to 1.5°). However in the case of a small screen, objects coming out the screen should be avoided because they might conflict with screen borders for the observer.
  - (B2) Vertical parallax should be null or very limited (20”) [9]; for this it is common to use parallel cameras and off-axis frustum as shown in Figure 11.

- (B3) Two neighboring planes at screen level, observed at the same time, should not have an important difference of depth.

- **(C)** To achieve better depth perception, the restituted vision should be isomorphic (if possible) to the vision of the real world. It is called orthostereoscopic vision. It has to enforce perspective and stereo depth perception laws. This implies three conditions:
  - (C1) The distance between the cameras should be equal to the distance between the eyes
  - (C2) Stereo images should not be stretched or flattened in the depth dimension which implies that the angles of the field of view should be equal at the acquisition and display levels.
  - (C3) The distance between the main observed object and the cameras should be equal to the distance between its image and the observer.

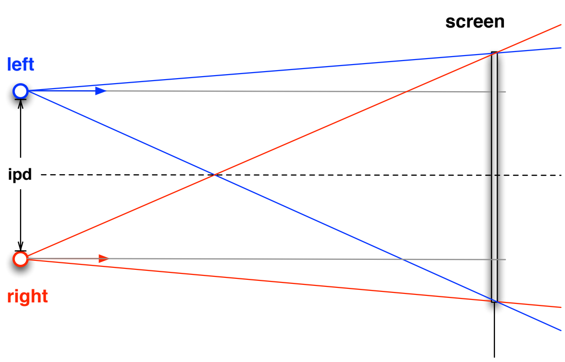


Figure 11. Parallel cameras and off-axis frustum.

C. Visual fatigue in stereoscopic immersion

In the previous sections, we have given an overview of the differences between natural 3D vision and 3D vision in virtual reality. Yet, stereo immersion remains a tiring experiment due to the differences between natural 3D vision and stereo images. In this section, we will elaborate on the visual strain caused by long stereo immersion: we will present other causes of visual fatigue in stereo and a few proposals to overcome this fatigue. Visual strain (or fatigue) is mainly caused by fusion limitations previously seen. Besides, it has been shown that visual fatigue is increasing when the human visual system is coming close to fusion limits [18].

Another common set of problems can be linked to *binocular rivalry*: one eye and thus one image is usually dominating the other one. This dominance can be modified by differences of contrast or luminance between the two images [19]. For example, using two video-projectors in a passive stereo installation can cause serious fatigue if their luminance is different [20]. Color differences (including presentation of anaglyph images) is also a source of fatigue.

In the previous section, we pointed out that head tracking was required for correct shape perception. As far as visual fatigue is concerned, it must also be said that latency (i.e. the time gap between a user action such as head motion and the result on the screen) is critical with respect to visual fatigue and more generally to cyber-sickness and virtual environments acceptance [21].

One major difference between most real-time computer generated images and real images is that the latter as we perceive them include a defocus blur. The defocus blur is a kind of message to the brain that tells not to try to fuse images. As defocus blur is usually not included in real-times rendering, the brain always tries to fuse the whole image causing visual fatigue.

Visual comfort and visual fatigue are two terms used interchangeably in the literature. However, eye strain is a measurable decrease in performance of the visual system while visual comfort remains a subjective assessment [22]. They are often linked as when there is eye strain, the observer feels his eyes as being uncomfortable, although the relationship between the two has not been completely clarified. In the following section, we will use both terms but more specifically visual comfort when dealing with subjective measurements and visual fatigue or eye strain for physiological measurements.

D. Stereoscopic comfort and image content

Besides the previous elements, there exists a relationship between fusion limits and the content of the images. More precisely, fusion limits are pushed forward when images contain low frequency content. This has been translated into a comfort index linked to frequency content of images by Wöpking [23]. Perrin [24] designed a comfort function based on Wöpking's study which is depicted in Fig. 12: it establishes a relationship between comfort $C(d, f)$, horizontal disparities d and spatial frequencies f which is shown in Eq. 1. As it was the case with Wöpking, the level of discomfort is expressed by a value ranging from -2 (very irritating) to +2 (imperceptible).

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

where $a = 0.010$, $d_0 = 18.9$, $k = 221.1$, and $k = 0.74$.

Several studies have been conducted in order to overcome visual fatigue in stereoscopic virtual environments in various conditions:

- *Still stereoscopic images:* Perrin [24] proposed to use wavelet transformation to identify the frequency content of a still stereoscopic image pair and carried out an experiment based on a skill test to confirm both Wöpking's result and the interest of removing high frequencies. However, wavelet transform was quite

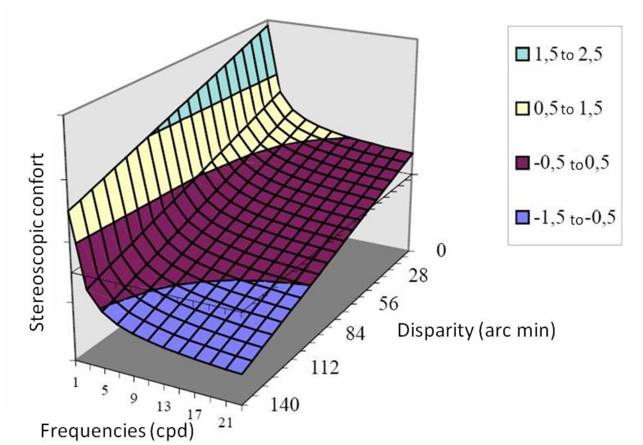


Figure 12. Visual comfort function [24], visual comfort decreases when spatial frequency and horizontal disparity increase. This function is an interpolation of Wöpking's results.

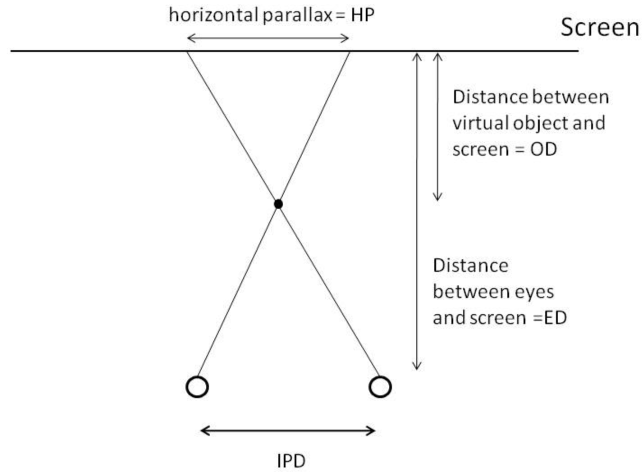


Figure 13. Horizontal parallax calculus with respect to the distance between the subject and the screen and between the virtual object and the screen.

costly. The cost was reduced in [25] but real-time performance was still not achieved. Some studies also experimented a depth-of-field effect for stereoscopic movies but only showed that removing high frequencies was not perceived negatively [26]. Other studies such as creating a depth-of-field effect on pre-computed images showed an increase in visual comfort although they were focused towards objects of interest rather than on the physical screen [27], [28].

- *Real-time monoscopic images*: Hillaire and colleagues studied the use of two kinds of blurring techniques: The first one was a "depth-of-field" blur which simulates the blurred perception of objects located before or behind the eye's focal point. The second one was the "peripheral blur" which simulates a blurred perception of objects when they are located in the peripheral sight area. They showed that the performance of video-games was not impacted and that the gamers were in favor of it being used [29]–[31].

Those studies show that is possible to seek for real-time images processing that would not impact performance and still enhance visual comfort. Thanks to GPU computation, we have been able to reach this goal [32]. We built a real-time blur algorithm using a sliding average on a graphics card. Based on equation (1), we deduce the upper frequency limit for a given comfort level:

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

As equation (1), $C(d, f)$ represents the visual comfort (between -2 and 2), d is the horizontal disparities and f is spatial frequencies. $a = -0.010$, $d_0 = 18.9$, $k = 221.1$ and $k' = -0.74$ are constant. In [32], we assumed that the comfort level must be greater than 0, but the whole process can be repeated with other comfort levels. Based on figure 13, we can compute HP the horizontal screen parallax with respect to OD the distance between the virtual object and the screen and ED the distance between the eyes and the screen:

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

Spatial frequencies (expressed in cycles per degree) are irrelevant to graphics cards that only know pixels, they must be translated to pixels and SD the number of pixels on screen for 1° can be computed as:

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

Given the real size w of the pixels on the screen, the blur is computed on a SD/w pixels window divided by the spatial frequency for a given disparity. The generated blur is thus progressive and a function of disparity. Those filters were implemented with "shaders" [33] in order to allow real-time processing of the images.

Using visual fatigue tests (and not only subjective comfort assessment), we showed evidence of the effectiveness of the approach with a user study that demonstrated that if task efficiency was not altered (it was not improved either), fatigue symptoms were significantly reduced: Punctum maximum of accommodation modification is reduced by this technique, ease of accommodation shows a difference of 1.77 cycles per minute (Fisher test: 99,45%) in favor of our technique. In the mean time stereoscopic acuity is not reduced at all conversely with standard stereoscopic rendering. Task effectiveness is also not altered but subjective measurements tend to show that if the task is perceived easier and less tiring, the virtual world remains more questionable on an aesthetics point of view.

IV. Conclusions

In this survey, we reviewed the issues raised by visual interfacing for Virtual Reality: they lie at the border between technological constraints of the interfaces and physiological characteristics of the human being. We mainly focused on depth perception in monoscopic and stereoscopic virtual environments through reviewing depth perception of the human being, visual interfaces types with their pros and cons before going a bit deeper into stereoscopic rendering. We showed it was different from natural 3D vision and gave a set of rules for providing correct stereo vision in VR applications as well as some hints to increase the viewer's comfort.

Yet, it is clear that VR interfaces can address several senses or motor actions of the human being and not only vision. Vision is a very complex sense but so are the others and technological constraints can be even more complex: for example, for haptic feedback, Brooks once showed that the frequency of both collision detection, deformations simulation and haptic rendering should at least 1Khz to provide the feeling of a rigid object [34]!

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