University of West Bohemia
Faculty of Applied Sciences
Department of Computer Science and Engineering

Diploma Thesis

Causes of Visual Fatigue and Its Improvements in Stereoscopy

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Abstract

This paper examines direct impact of stereoscopic images on comfort and state of heath of a viewer. Main causes of visual fatigue and other side effects related to it are presented. Also, basics of stereoscopy, technological principles of three-dimensional images reproduction and attitudes and results of similar works are given in a synoptic arrangement. This theoretical background is supported by number of our own practical experiments bringing new outcomes or highlighting the already known ones.

Acknowledgements

I would like to express my thanks to everyone who supported me during my work on this paper especially to my supervisor prof. Skala, who gave me a lot of valuable advices and most importantly an opportunity to be a part of such interesting project, to my colleagues Petr Čížek, Ricardo Santos and Zbyněk Novotný working on a similar projects for very helpful and clarifying discussions about a problem. A special thanks belongs to my very good friend Zbyněk Novotný who was the one who let me use the stereo-application for my experiments and include it to my work. Last but not least are all the people participating on my experiments particularly all PhD. students of computer graphics laboratory at Department of Computer Science and Engineering

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Statement

I hereby declare that this diploma thesis is completely my own work and that I used only the cited sources.

Pilsen ....
František Mikšíček

1 Introduction

Stereoscopy as an important part of computer graphics becomes involved in many fields of human pursuance at the beginning of 21st century. ‘Stereo’ is a Greek work meaning ‘spatial’ or ‘three-dimensional’. Stereoscopy deals with creating of spatial images which provide us with seeing depth in artificial scenes so that the one feels like looking at a real scene.

Advanced technologies help people with studies, research, in medicine or entertaining industry. Devices utilizing such devices have the task of simulating real visual conditions projected in front of the viewer. In comparison to 2D technologies, 3D devices provide the user with perception of depth thus the operation can be performed with higher accuracy and promptness. However, various imperfections of such representations could seriously influence the image output quality or even viewing comfort of users during observation. Three-dimensional images can be created with no problem in present days, although faultless images creation is mostly a matter of a great deal of stereoscopy knowledge and application of very sophisticated and expensive apparatuses for visual representation and other accessories.

This paper describes a synoptic arrangement of the methods and experiments which were conducted with the goal of investigation and improvement of viewing conditions while watching an artificial 3D scene, presented by some of the current techniques of stereoscopic graphics. Very much of a research has already been carried out in this field in past few years. Our aim is to summarize attitudes and results of these papers and contribute by putting forward and conducting some of our experiments and identifying problems than may occur in terms of visual strain and fatigue.

This work is a part of 48-month project on 3DTV (https://www.3dtv-research.org) started in the beginning of 2004. A association of 19 institutions led by Bilkent University in Turkey has been working on 3D display present in our everyday life. The University of West Bohemia in Czech Republic is one of the institutions involved, having Prof. Ing. Václav Skala CSc. as responsible supervising person in this university (http://3dtv.zcu.cz).

2 Basics

2.1 A little bit of history

The idea of stereoscopy preceded both photography and sound reproduction. The very well known artist Leonardo da Vinci dealt with the idea of perception the world through two different views corresponding to our eyes. The task was to deliver different picture to each eye by some technical device.

The first such device called a stereoscope was designed by English physicist Charles Wheatstone. On June 21, 1833 he lectured to the Royal Society in London on his discoveries concerning stereoscopic phenomena. He supported his accidental discovery with drawn pictures, and developed the first stereoscopic viewer, which worked with mirrors.

On August 19, 1839, the Frenchman Daguerre disclosed his method of generating permanent photographic pictures by making photographs by camera obscura. It became possible not only to draw stereograms, but to photograph them as well. Rising popularity of camera, made this technology very popular among enthusiasts.

Thanks to insufficient information basis many mistakes occurred resulting in incorrect stereograms causing headaches to the observers. The English physicist David Brewster improved the stereoscope in 1849 and so created the first true stereo camera with two lenses. In 1855 the Frenchman Barnard invented the first frontal stereo attachment constructed with mirrors for single lens cameras. The stereo viewer (stereoscope) was further developed by the Germans, Helmholtz and Pulfrich.

The golden age of stereography had begun. From 1860 to the 1930's, the stereo cards documented life of the time and important events. A variety of viewers became available, from the simple Holmes viewer to cabinet-type viewers which could store fifty or so positives.

One of the first movies ever provided to the cinema audience was the French film “L’Arrivée du Train” in 1903, which showed a train running towards the movie screen.

Purportedly, some observers were so convinced by the 3D sensation that some of them ran out of the building screaming.

In the year 1936 three approaches were discovered for production of polarization filters (Bernauer, Kaesemann, Land and Mahler). Thus, picture separation became possible even in colour photographs. With their help, the amateur could project his stereo slides onto a silver projection screen. This, of course, generated a lot of interest, and led to the construction of true stereo projectors with two lenses.

Many technologies delivering depth sensation have been developed so far and many studies have been conducted to investigate all possible characters of this vast field of science. Different attitudes offer their different assets and drawbacks. Today, the stereoscopic technology is widely used in movie theatres IMAX (first performance on January 1998) or amusement parks. Of course stereoscopy is used for scientific purposes, where closer interaction between man and viewed scene is needed helping the one to navigate through the space more easily. However, there are still many issues waiting to be solved before we find the reconstructed 3D scene indistinguishable from the real one.[2][3]

2.2 Human optical system

Since this work deals with the problem of visual strain and fatigue, I found quite useful to write a brief introduction to human optical system in terms of medical science.

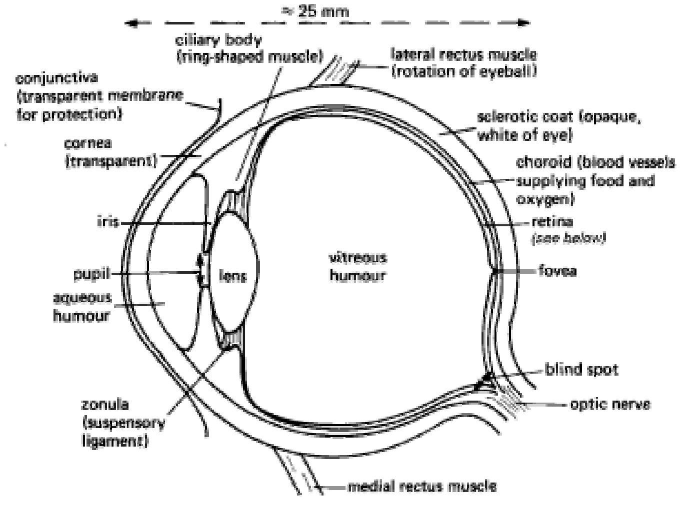


Fig. 3.1 Anatomy of the human eye (taken from [4])

The human optical system consists of a pair of eyes typically about 63,5 mm apart (also known as *interocular distance*), thus making different perspective view for either of them.

Light reflected off the external objects. This light enters eye through the cornea and the lens. Ultimately it will reach retina, light sensitive part of the eye. The retina consists of photoreceptors called rod and cone. The rods are sensitive to low light and cons handle colour vision and detail. Both retina images are perceived up side down and transferred to the brain by optical nerves. Those two images are blended into one compound, final picture which helps us to perceive depth. This ability to perceive three-dimensional depth due to the distance of person and objects is called *stereopsis*. Stereopsis can be described as a perception of depth produced by *binocular retinal disparity*, hence it is simply a member of set of properties commonly referred to as *visual depth cues*. These properties are often classified as being monocular or binocular and physiological or psychological.[1][11] See more in chapter 2.3.

2.2.1 Human optical system drawbacks

Human visual system is ‘technically’ a way far away from modern optical systems used nowadays. From a physical point of view, eye is quite an imperfect optical device. Cornea, aqueous humour, lens, vitreous humour, which make up together a dioptric eye apparatus, show all possible drawbacks of an uncorrected lens system: spherical and chromatic aberration, astigmatism of oblique rays, coma and distortion.

- **Spherical aberration**

It is a shortcoming of the lens caused by homocentric rays, which are emitted from one point on the lens axis or from infinity, not to cross at one point (= focal point).

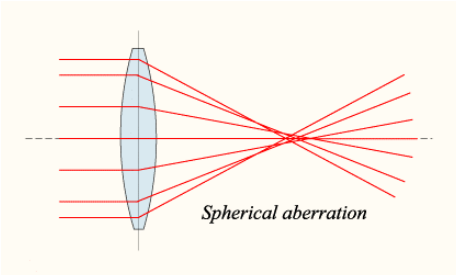


Fig. 3.2 Spherical aberration (taken from [5])

- **Chromatic aberration**

The lens acts partly as a prism. Thus causing colour dispersion of the penetrating light rays. Converging lens makes the violet and red light component to lie nearest and furthest from the lens centre respectively.

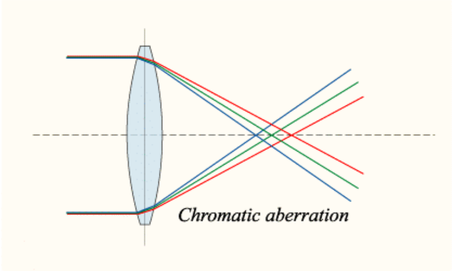


Fig. 3.3 Chromatic aberration (taken from [6])

- **Astigmatism of oblique rays**

When a conical beam of rays, coming out of one off-axis point, fall on the lens, the traversed rays do not have one common focal point. In the extreme positions the focal points are line-shaped (focal line) and perpendicular to each other.

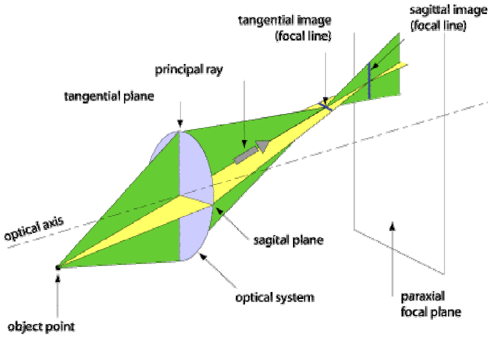


Fig. 3.4 Astigmatism of oblique rays (taken from [7])

- **Coma**

Another type of aberration. It occurs when an object off the lens optical axis is projected. Parallel rays, traversing the lens at an angle to the axis θ, do not intersect at one point thus causing blurred image as shown in Fig. 3.5.

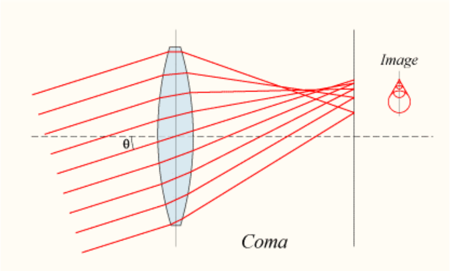


Fig. 3.5 Coma (taken from [8])

- **Distortion**

As a distortion we describe a lens' imperfectness, which makes points lying further from the lens centre to be magnified more than point lying nearer. Barrel distortion appears when diverging lens was used and pincushion distortion appears in case of the usage of converging lens.

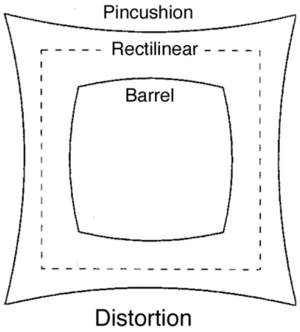


Fig. 3.6 Types of distortion (taken from [9])

Each eye has a little drawback in terms of the visual output. There is a fovea on a retina of every healthy eye causing a blind spot in a viewing field. Brain is capable of dealing with it by some kind of innate colour interpolation in the affected place and thanks to the overlapping viewing fields the phenomenon is almost completely suppressed. (see Fig. 3.14)

2.2.2 Ideal lens

Lens of the eye is not a perfect optical device, but ignoring those facts described above we can talk about *ideal lens.* [10]

This imaginary device has following attributes:

- All light rays radiating from a point of light (an object point), at the object distance from the lens, are refracted by the lens through one point (the image point at the image distance from the lens).
- Rays hitting the lens at its centre (the blue line) are not refracted.
- Rays hitting the lens perpendicularly to the lens plane (the red line) are refracted through its focus.

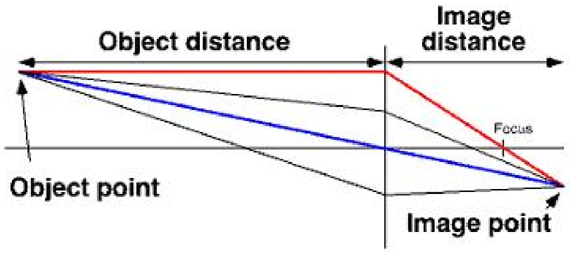


Fig. 3.7 Ideal lens (taken from http://www.neuro.uu.se/fysiologi/gu/nbb/lectures/EyeOptics.html)

Applying Euclidean geometry to the ideal lens, we can put forward the lens formula:

$$\frac{1}{\text{object distance}} + \frac{1}{\text{image distance}} = \text{lens power} \qquad (1)$$

Sometimes, we can run into negative object distance. For that reason we slightly alter the formula with a minus sign in front of the ‘object distance’ value.

2.2.3 Visual acuity

Visual acuity is a measure which helps determine if the object of particular size and distance is seen sharp and clear. It is represented by angle (mostly min of arc - a minute of arc is 1/60 of a degree) containing the focused object.

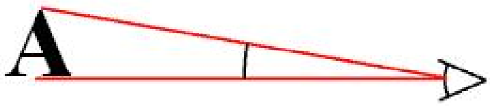


Fig. 3.8 Visual acuity

Obviously, if this angle gets too small, the eye cannot distinguish top and bottom from each other. The smallest angle which still allows the eye to see sharp object, is called the *resolution angle*. The visual acuity is defined as the inverse of the *resolution angle*. Thus, the "typical" resolution angle is 1/60 of a degree.

Very close term is *depth of focus*. This term refers to the fact that, since the accuracy of the retina is not unlimited it does not matter if the image on the retina is a little blurred. Therefore 1.0 visual acuity is possible not only at the perfect distance from the eye, but within a range around it. In terms of optical strength the limit of seeing sharp objects is around 0.25 dioptres. Depth of focus of the other optical devices can be variable though, from the values near to zero dioptres to infinity. In the second case the whole scene is sharp regardless the distance from the scanning device.

All subject participating the certain tests had normal or corrected-to-normal visual acuity.

2.2.4 Spatial frequency

Spatial frequency is a term which we can come across in stereoscopy field very frequently. Basically it concerns a measure of visual detail level. High values carry information about fine details whereas low values carry information about coarse details (object shapes). Example images show the whole spectrum of spatial frequencies from low values on the left to high values on the right of each image (see Fig. 3.9). Sensitivity of particular frequency is closely related to the contrast of a presented picture. The lower the contrast, the lower the upper limit of perceptible spatial frequency. The effect is depicted in the left part of Fig. 3.9, where the contrast is changed in the vertical direction. This dependence is described by the *contrast sensitivity function*. A typical sensitivity function is shown in the Fig. 3.10. The sensitivity peaks at about 3 cycles per degree, dropping rapidly till the value of about 50 cycles per degree, where the fine pattern becomes indistinguishable by human eye.

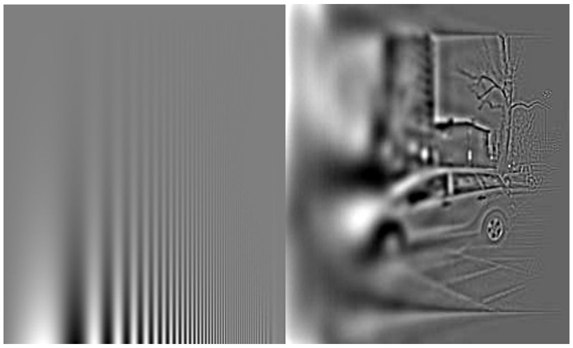


Fig. 3.9 Spatial frequency in the pictures.(taken from [35])

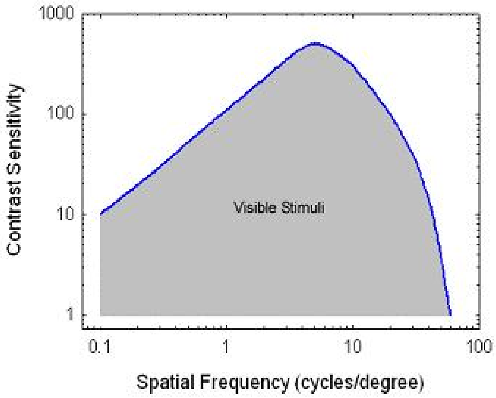
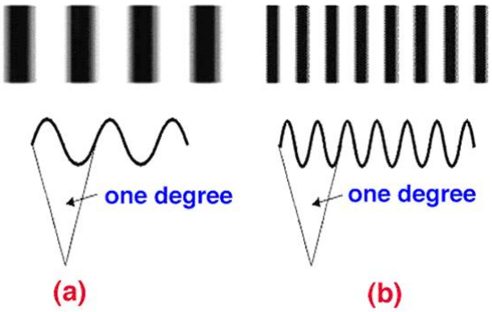


Fig. 3.10 Human contrast sensitivity.(taken from [28])

Spatial frequency is a measure of number of cycles subtending the eye per one degree (see Fig. 3.11). To make these associations more comprehensible, we can turn this measure into more common one. Having viewing distance 50 cm and spatial frequency of maximum response 3 cycles per degree, we can calculate physical spacing between the image cycles. One degree at this distance translates, according to the formula (2), to 50 tan(1deg.) = 0.87 cm. Thus the spatial frequency of maximum response f_{max} = 3 cycles/0.87 cm = 3.44 cycles/cm at this viewing distance.



$$f_{\max} = \frac{f}{d \cdot \tan(\alpha)} \tag{2}$$

Fig. 3.11 Spatial frequency.(a)One cycle per degree (b) Two cycles per degree (taken from [36])

2.2.5 Accommodation & convergence relation

Accommodation is a capability of the eye to focus on an object we are looking at through altering shape of eye lenses by contracting the ciliary muscle. This ability is changing throughout the lifetime and it deteriorates with age. The difference between optical system power of the eye in maximum and minimum accommodation is the *power of optics*. It is measured in dioptres and is equal to the value of *near point* (*punctum proximum*). Near

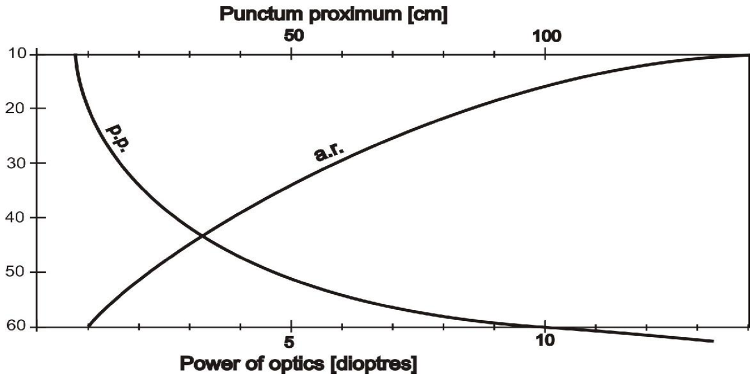


Fig. 3.12 Dependence of the power of optics and near point on the age. Example: in 10 years of age the punctum proximum is in the distance of 7 cm from the eye, power of optics is 100/7 = 14 dptr.

point is the smallest distance at which eyes can see sharply. Changes in accommodation range along with changes of the near point distance were expressed by Donders in very well known chart (see Fig. 3.12).

There is also *accommodation range* related to the term *power of optics*. It represents range, in which the objects are seen sharp (focused). It is a difference between near and far point expressed in units of length. It decreases with age as well.

Convergence describes the eyes' ability to divert eye optical axes horizontally in inward or outward direction. The aim is to fuse two slightly shifted images of gazed object to match together. It is done by particular eye muscles rotating the eyeball. The near point in terms of convergence is meant the closest point which is still possible to perceive like one image.

Miosis (smaller pupil), which improves the visual acuity (depth of focus), by working as an aperture for the eye lens. The aperture is a means for controlling depth of focus of the eye. The smaller the gap is the higher the value of the depth of focus and the less light passes through to the eye. The range of in-focus (from D_1 to D_2) and the focal depth ΔD (= D_2 -D_1) are given by

(3) $D_1 = \frac{sld}{ld + s\delta}$ (4) $D_1 = \frac{sld}{ld + s\delta}$ (5) $\Delta D = \frac{2s^2 l\delta d}{(ld)^2 + (s\delta)^2}$

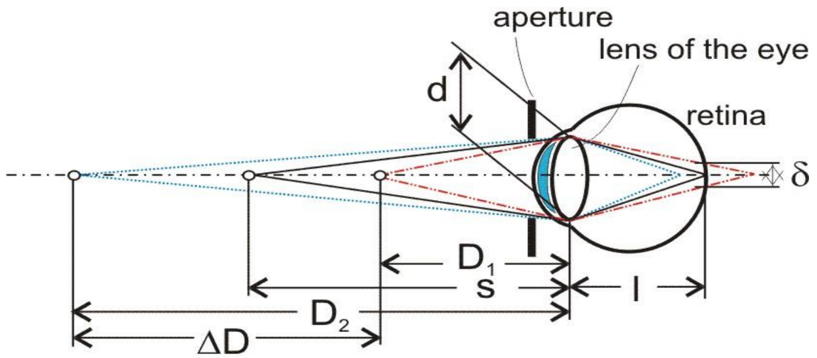


Fig. 3.13 Relationship between aperture size and depth of focus of the eye.

Where (according to the Fig. 3.13) *s* is a distance between a gazed point and centre of lens, *l* is a distance between the centre of lens and retina, *d* is a projected disparity on the retina and *d* is a diameter of the aperture stop.

There are many drawbacks and imperfections of our optical apparatus. Mostly it is possible to mend those optical impairments by additional means like filters, lenses, apertures etc. From now on we will be talking only about the conditions unaffected by any of those defects or at least conditions meeting the requirements currently needed i.e. subjects needed for experiments possessed emmetropic or normal vision having no problems with fusing binocular images or focusing on the particular distances.

Accommodation and convergence are interconnected. Their values are changing proportionally in relation to each other. They always adjust for seeing at the same point of interest – the point of convergence and accommodation is identical. Disrupting of this relation can lead to double vision, faulty judgment of distance or the like thus causing eye strain. The relationship is described by the closed-loop adaptive optics of the human eye which we will describe in chapter 2.7.

2.3 Depth perception

In order to figure out where an object is in the scene, we need a way of judging depth in our visual environment. The sensation of reality in a scene or picture occurs because of depth perception, which is defined as an ability to judge spatial relationships in three-dimensional world. Our eyes only have two-dimensional retina images and no special third component for depth perception. This requires an interpretation of our physiological cues that leads to useful "perception". Our surrounding gives us various hints to gauge its proportions commonly called *visual depth cues*. The difference in gaze directions of the left and right eye is a measure of convergence, which along with accommodation, makes two main sources of depth perception and recognition. But it is not true, that our depth vision must rely only on stereopsis. Every depth cue has its own specific importance both those using two eyes (*binocular cues*) or one eye (*monocular cues*).

Depth perception is possessed by those animals with overlapping optical fields (see Fig. 3.14), acting as a range finder for objects within reach. Humans have wide-field fully coloured peripheral vision (*field of view* - FOV) practically over 180 degrees of arc horizontally, the part of which is dedicated to full stereo-vision (120 degrees wide), and 150 degrees of arc vertically.

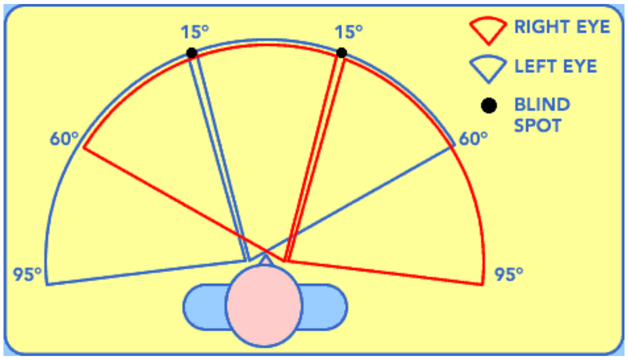


Fig. 3.14 Human visual field. Stereopsis occurs in the field of view, where both left and right eye field are overlapping. (taken from [12])

However, this ability highly depends on precise simultaneous projection of scene on both retinas, and any imperfection or disruption can lead to depth perception disorder or ambiguity.

2.4 Binocular vision

Binocular vision is a result of two eyes seeing a scene from different positions and angles. The closer the gazed object is the more significant is the image difference result relatively to the depth. There is a simple "thumb technique", which very illustratively demonstrates basic facts about our binocular vision, like different eye gaze angles or binocular disparity. Hold your thumb in front of your face and focus on it. Now alternately close and open your

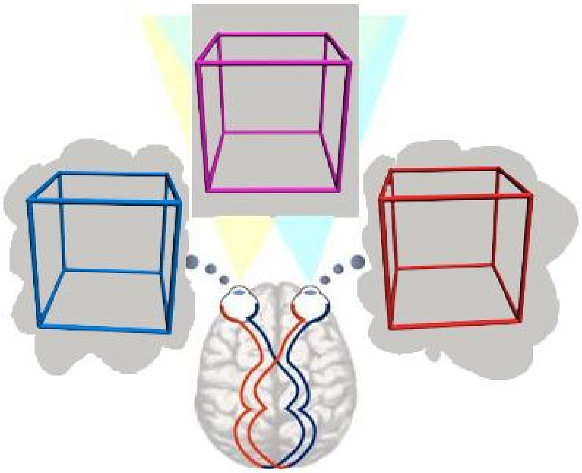


Fig. 3.15 Binocular vision of wire cube. Left (blue) and right (red) eye images blend into one three-dimensional object (magenta).

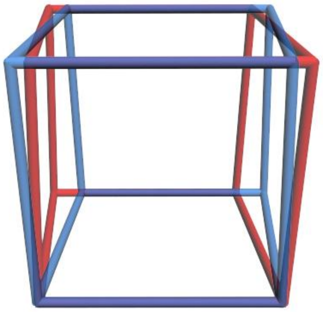


Fig. 3.16 Blended images in the brain. Crossed object boundaries on the sides depict zero disparity.

eyes so that only one eye is opened at a time. You can notice that the unfocused background is moving according to the gaze angle of the active eye. Also you can put both thumbs in front of your face one behind another about 30 cm apart, and focus on one of them, you can see double vision (diplopia, disparity) of the unfocused one.

When looking at the object we use eye muscles to get the separate images overlapped. The mind's ability to create three-dimensional visual world out of two separate images is called *fusion* and its outcome is *stereopsis* giving the immediate impression of depth. It simply suppresses the horizontal shifting (*disparity*) of the scene image, so that the gazed object can be perceived single. Fusion takes place when the objects (visual outcome) contain enough corresponding points present in both images. If some visual conflict occurs it can cause suppression, superimposition or binocular ("retinal") rivalry [15]. It is not necessary for single object vision to achieve the *zero disparity*, the image difference lower than some threshold is still seen as single. The largest disparity at which fusion occurs is called the disparity limit of fusion. The disparity limit of fusion depends directly on the stimulus size or scale. Thus it needn't to be a problem to see complete object extending far to depth (see Fig. 3.16) as long as the limits are not exceeded.

An artificial inducing of the binocular vision is a means of delivering different image to each eye. It differs for every technical apparatus as well as the principle of visual representing images themselves.

2.5 Perception cues

There are many clues supporting perception of depth, but stereopsis is the most reliable and overrides all others. Stereopsis itself cannot occur monocularly though. Our visual system uses wide variety of visual cues to determine scene depth. The level of stimulation of these particular cues is essential for the perception credibility of the artificially created spatial environment. High quality stimulation is the crucial factor for creating persuasive depth stimulating images.

There are two main kinds of the cues. For one it is necessary to use both eyes while viewing the world around. These cues are termed *binocular cues* of depth. The set of clues applied for a viewing of scene through only one eye is called *monocular cues*.

2.5.1 Monocular cues

For perceiving the monocular, or extrastereoscopic, depth cues, we need only one eye. Even though we are using both eyes, this set of cues still significantly affects our depth perception. Many of them are experience dependent. This means, that our brain is reconstructing the scene depth according to the former experience i.e. the one knows, how the common car is big, so he can estimate the distance from it by the size of the object image, or commonly known object shape can help us to figure out how the scene looks like even at places where we cannot see everything. The precision of monocular depth perception is highly variable though, depending on stimulus, lighting and motion of the object, but is generally accepted to be inferior to binocular depth perception (stereopsis).

This set of cues is less convincing for our senses, than the other one, all the more it is widely used in computer industry nowadays thanks to its easy application in practice.

- **Accommodation (blurring)** is closely linked with the convergence but even though it occurs while using both eyes, it is still a monocular cue. The depth is obtained from the ciliary muscles tension affecting shape of the lens allowing us to focus on objects in different distances. As we focus on distant objects, our lens is made thinner, and as we focus on near objects, our lens is made thicker. Objects out of the depth of focus are blurred.

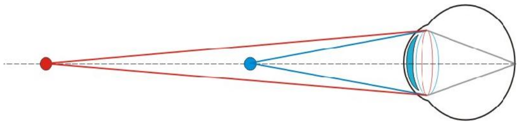


Fig. 3.17 Eye accommodation on two objects shifted in depth.

- **Size** has quite obvious impact on depth perception. Bigger objects seem to be closer to the observer than the farther ones mainly due to our previous knowledge of their real size. So different size may represent different position in the scene depth.

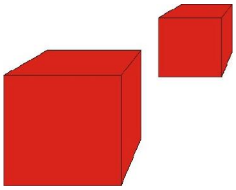


Fig. 3.18 Size cue.

- **Motion parallax** refers to the object movement (or just its parts) in different velocity and/or direction at different spatial depth of the scene. The example is shown in figure 2.12 (arrows depict direction and relative velocity of objects in the scene). If the one focuses on the object in the middle of the scene and moves, objects in the front move right the opposite direction than the objects in the rear. Also objects farther away from the point of focus move faster than those ones closer.

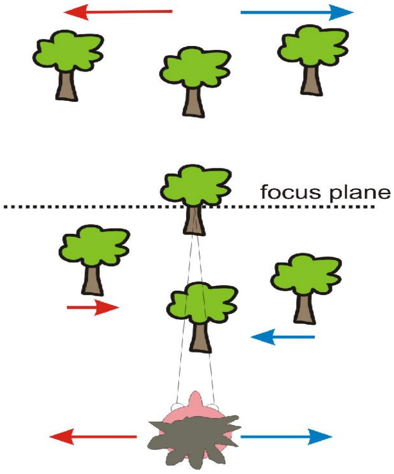


Fig. 3.19 Motion parallax cue.

- **Density** is in a sense an equivalent of the size cue. The higher density of objects distribution the farther they seem to be from us. It may also appear when an object covered with a texture (regular for the best) reaches far to the depth.

Fig. 3.20 Density cue.

- **Intersection (overlapping)** is one of the most powerful cues (and perhaps the most primitive), which effectively overrides the rest. That's why it is necessary to use this cue very cautiously. Objects that are in front of other objects may partially block our view of the rearmost object. Because we know what shape the object should have, and because we see only part of it, we interpret the obstructed object as being farther away.

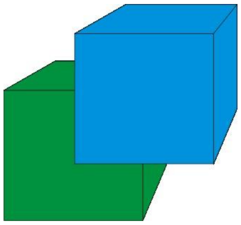


Fig. 3.21 Interposition cue.

- **Luminance** affects depth perception in terms of different brightness of the object surface. If the light from the observer traverse the scene to the object, the surface of the nearer one will be, because of the light dispersion, brighter than the surface of the farther one.

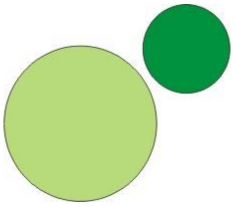


Fig. 3.22 Luminance cue.

- **Shade (shadow)** is one of the most evident monocular cues. It gives us a clue how to determine very easily the placement of the scene objects and their particular shapes. If the object is covered by the shadow it is perceived to be further away (in the direction from light) than the object casting the shadow.

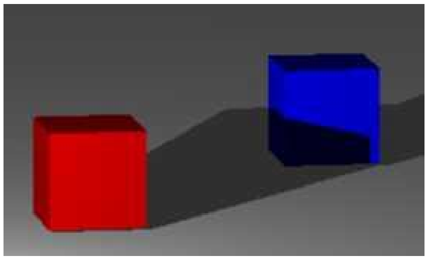


Fig. 3.23 Shadow cue (taken from [16]).

- **Air-perspective (haze)** cue uses the fact, that object surface loses its sharpness, colour, and contrast within the increasing distance from the observer. The farther the object is in the scene the more blurred, colour faded, and with less contrast the object will be.

Fig. 3.24 Air-perspective (haze) cue.

- **Colour** helps us to ascertain the object depth through using the innate eye drawback called chromatic aberration (see chapter 2.2.1). Throughout the light colour spectrum the blue appears to be the most in the rear, and on the contrary the red appears to be the most in the front of the scene. This phenomenon is also used in 3D display technique called Chromadepth (see chapter 2.8.2).

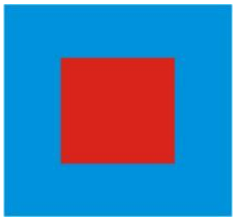


Fig. 3.25 Colour cue.

- **Relative height** cue causes that the object closer to the horizon is perceived as farther away, and the object further from the horizon is perceived as closer.

Fig. 3.26 Relative height cue (taken from [17])

- **Linear perspective** is noticeable when two parallel lines going from us to the rear of the scene. All the parallel lines lengthen to the infinity cross at one point (at the horizon line) called vanishing point. It is the relationship between the background and the foreground objects. The wider the viewing angle of the camera the more significant the size difference of the retinal images between distant and nearby objects will be. This is an easy way how to enhance the image depth.

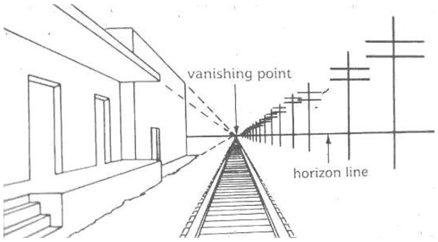


Fig. 3.27 Linear perspective cue. (taken from [18])

- **Texture** is the monocular cue provided by our proximity to an object. All surfaces have a texture, and as the surface goes into the distance, it becomes smoother and finer, with less distinguishable details. The more detail of the texture we are able to see, the closer the object seems to be for us.

Fig. 3.28 Texture cue. Picture of a sand dune from far and near.

2.5.2 Binocular cues

The binocular depth cues, or cues that require both eyes, arise from using two separated eyes in order to view the world around. They are considered to be much stronger in providing us with depth perception, than the monocular cues. This strength comes out of the apparent sophistication of judging depth in a visual stimulus by using the innate brain ability to separate out the depth from two slightly different retinal images and the differential feedback from eye muscles from accommodation & convergence on objects at different distances, whereas the monocular cues are mostly based on our experience with the surroundings.

Binocular disparity

Our optical system uses two different images projected on the retinas to get 3D image of scene we are looking at. The binocular disparity or also retinal disparity grants us important information about depth relationships between objects. Actually, this powerful ability alone provides us with enough information to extract depth. There is also a specific division of this term to *vertical* and *horizontal* disparity. The horizontal disparity is essential for evoking stereoscopic effect, while the vertical one is created just in artificial conditions (technical stereoscopic apparatuses) deteriorating the viewing perception. From now on we will call *horizontal disparity* just *disparity* unless said otherwise.

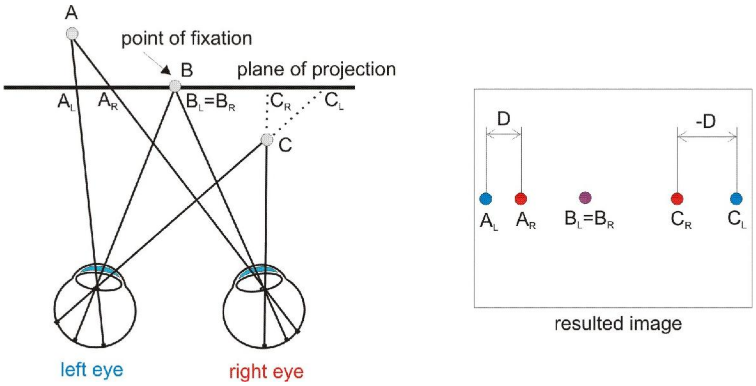


Fig. 3.29 Geometry of binocular projection (left) and the definition of binocular disparity (disparity). Images gained by left and right eye are blend into one resulted image.

While looking at a scene, we rotate (converge - see chapter 2.2.5) our eyes horizontally to fuse the projected images in order to make the focused object single. The disparities result from surface shape and depth as well as the direction and distance of gaze, and the torsion of the eyes. When the object (or just its part) is focused and thus his disparity is zero, the other objects in the scene may cause the disparity according to the specific conditions mentioned above. The degree of disparity between the images depends on the parallactic (convergence) angle. This is the distance related angle formed by the optical axes of each eye converging on an object. The resulted disparity is measured as a difference between the binocular parallaxes of the two points in the scene (mostly in terms of minutes of arc). This value is defined (the angles are measured in respect to the parallel eye axes) as:

$$(6) \qquad Disparity = (\alpha_{1L} - \alpha_{1R}) - (\alpha_{2L} - \alpha_{2R}) \qquad (7) \qquad Disparity = \frac{d_e l_i}{l_r^2}$$

Disparity is usually expressed as a difference between two angles but angular disparity can be also estimated using formula (7). The values and their description can be found in Fig. 3.36. If all the length units will be the same (millimetres, metres …) the count will be in radians.

The circle (or curved line) in which are situated all points perceived as single, while focusing on the point in the space – *point of fixation*, is called *horopter* or *isodisparity* *circle* (see Fig. 3.30). The geometrical equivalent of equation (7) for the zero disparity value is that angles formed by two nodal points and the other two points in space are equal ($\alpha_L=\alpha_R$). The further from the horopter the second point is, the greater the anatomical disparity on the retinas.

But there is a range of disparities that yield binocular singleness. *Panum's area* defines a strip around the horopter where the objects seem to be single – the disparity is within the limits which our brain considers to be a threshold of a single/double view (see Fig. 3.31). This threshold disparity value extends usually about 15 min of arc. Theoretical horopter is the Vieth-Muller circle passing through the fixated point and the optic centres of the two eyes (*nodal points*) while practically empirical horopter is a vertically skewed curve going through the fixation point. Points lying outside the Panum's area are perceived as double. The points lying inside the circle causes diplopia seen as a *crossed disparity* (left eye image is seen on the right side from the right eye image and vice versa) and the points lying outside the circle causes an *uncrossed disparity*. Crossed disparity causes object to appear closer to the observer compared to the fixation point – also known as negative parallax, while for uncrossed disparity the object appears to be further away than the fixation point – also known as positive parallax (see chapter 2.6).

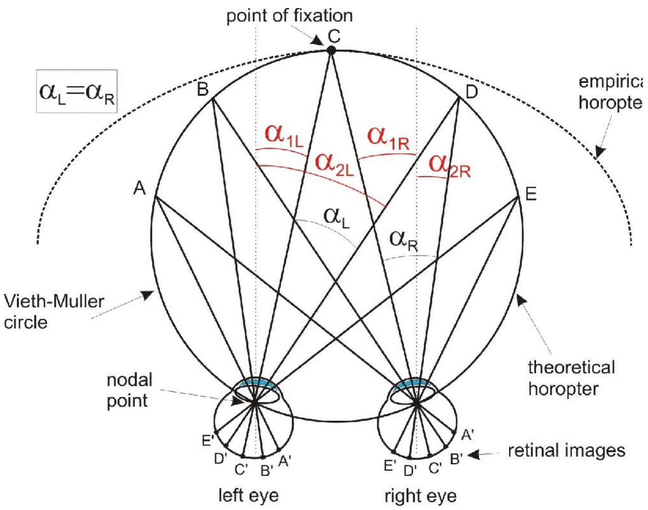


Fig. 3.30 Theoretical and empirical horopter. The points A to E are projected single as long as the condition $\alpha_L=\alpha_R$ is met.

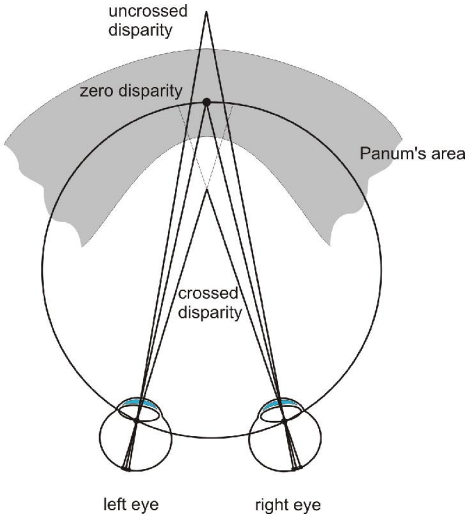


Fig. 3.31 Panum's area. The disparity differentiates by sign of the result. Crossed/uncrossed disparity yields negative/positive value of disparity.

Putting the fusion eye ability into the distance relation, we get the following diagram showing, how narrow this region in three-dimensional space is.

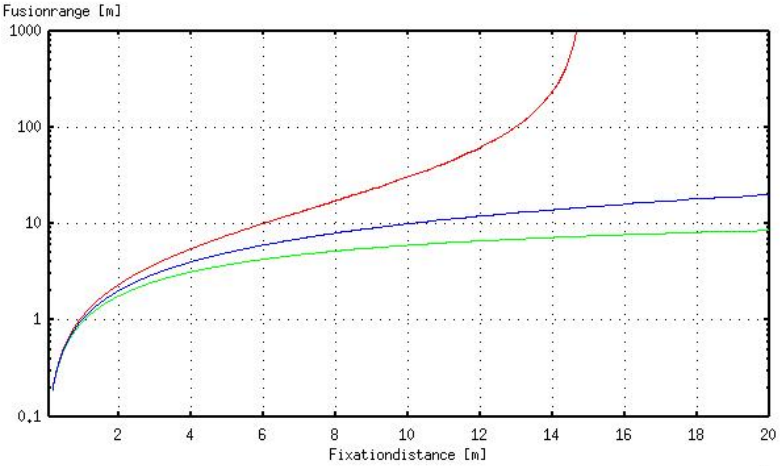


Fig. 3.32 Limited fusion range in the three-dimensional space. The near (green line) and far (red line) borders of the fusion area around the fixation point (blue line). (taken from [14])

Binocular disparity is closely related to the *binocular parallax* and these terms are often interchanged. Parallax relates to the physical difference of two images on the display, whereas the disparity is the image difference on the retinas. Disparity itself results in depth sensation called *stereopsis*. Parallax can be given in terms of length measure, between two corresponding points, or angular measure (see equation (7)).

Convergence

This cue in conjunction with the *accommodation* is also very often considered as a special set of depth evoking inputs called *oculomotor cues*. Combining visual and proprioceptive information from the eye helps us to derive information related to distance. Focusing and converging come in close connection with location of the gazed point. This is happening through using the particular eye muscles (see chapter 2.2) and feedback from the nerve centre. Our brain is processing the slight divergence in muscular tension, and then correlating that information with how far a given object is away from us. The degree of the eye convergence, along with the interocular distance (usually 2.5 inches for adult), provides a measure of the absolute distance between the observer and the stimulus. Although, if the objects are far away the eye axes become almost parallel and the amount of convergence is insignificant. For distances greater than about 20 metres, convergence is not effective in aiding of the perception of depth.

Naturally, there are physical constraints of our visual system restricting the eye convergence to the certain limits. For more see chapter 4.4.

2.5.3 Different cue sensitivities

While watching the artificial 3D scene, all the conditions influencing the intake of depth information must match to the conditions encountered in reality. As the depth cues are the pillars of depth perception, a study comparing the conditions of their usage is necessary. There has been an experiment conducted on the topic of monocular and binocular cue sensitivities in relation to the distance by using the characteristics of the visual input of the information for visual depth perception [13].

The examined cues were: convergence, accommodation, binocular parallax, motion parallax, brightness, texture, size and air-perspective contrast. The author proposes a common scale for evaluating the availability of depth cue, which is defined as a ratio D/ΔD of the viewing distance D to the detection threshold ΔD of depth difference (depth threshold). We call this ratio scale “depth sensitivity” of vision. In this way, it is possible to compare various cues with each other, which was impossible before, thanks to the different physical attributes of particular cues.

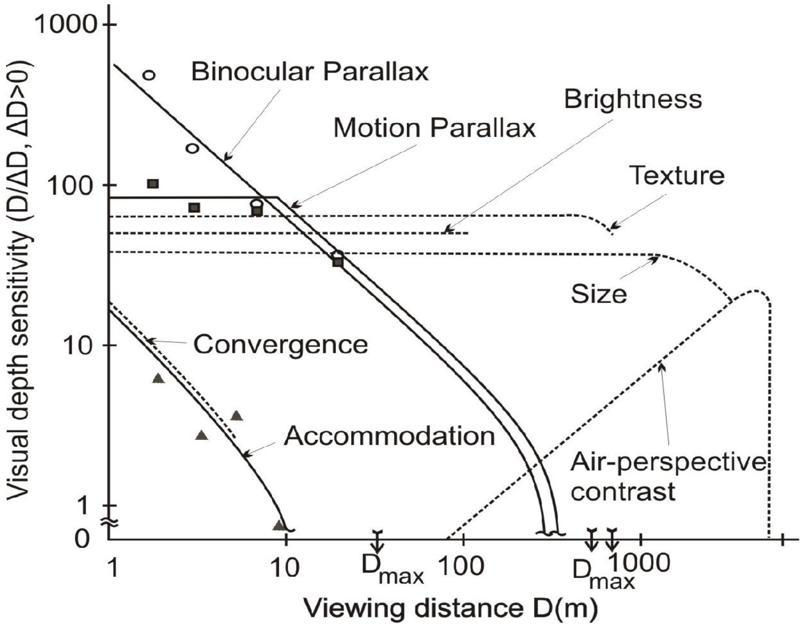


Fig. 3.33 Depth sensitivities of various cues for visual depth perception as a function of viewing distance. Symbols (▲, ■, ○) indicate the averages of five measurements of one particular subject.

Some conclusions have been deduced from experiments and observations (following lines are cited from [13]):

a) The depth sensitivity relative to binocular parallax is highest at a distance of up to 10 m.
b) The depth sensitivity to motion parallax is effective, and this sensitivity on motion at the optimum velocity exceeds that of binocular parallax at a distance greater than 10 m.
c) The cues from accommodation and convergence are effective for the relative depth perception only at a distance of less than 1 m, but are effective for the absolute depth perception at longer distances.
d) The pictorial cues are effective even at long distances, and the sharp edge of pictures, and clear texture, shade and gloss of the surface on objects strengthen the sensation of depth.
e) The effects of these cues work together and combine spatially on the wide visual field.

The following conditions to decrease the picture flatness of 2D pictures and to reinforce the depth perception in the picture were found (following lines are cited from [13]):

a) The effects of binocular parallax must be decreased.
b) The distance of convergence and accommodation must be close to the actual distance of the objects in the picture.
c) The frame of the display must be separated from the images peripherally or depth-wise.
d) There must be many monocular pictorial cues including the projection of three-dimensional moving objects.

2.6 Types of parallax

There are four types of parallaxes which could possibly emerge in case of looking at the artificial scene on display:

a) *Zero parallax* - is the case when pictures on the screen lay on the top of each other. The image difference is zero and eye axes converge right at the plane of focus. This situation as the only one equals to the observation of the real scene, where focused point always corresponds to the convergence point.

b) *Positive parallax* - also known as *uncrossed parallax*. The position of convergence point is placed behind the projection screen so the infinity is also counted. In this case the optical axes are parallel (the same as if we look at very distant objects in the real world) and the distance of two corresponding images and interocular distance d_e are equal. The position of the images corresponds to the position of the eyes – left eye image on the left side, right eye image on the right side.

c) *Negative parallax* - also known as *crossed parallax*. The convergence point is in front of the projection screen. Image separation depends on the convergence angle and distance of the observer from the display. Thus it can be more than distance d_e. Position of the images is swapped - left eye image on the right side, right eye image on the left side.

d) *Positive diverged parallax* - doesn't occur when looking at the real world. The optical axes are diverging thanks to the artificial conditions induced by image separation exceeding the distance between eyes. This case can cause serious visual inconvenience for the observers.

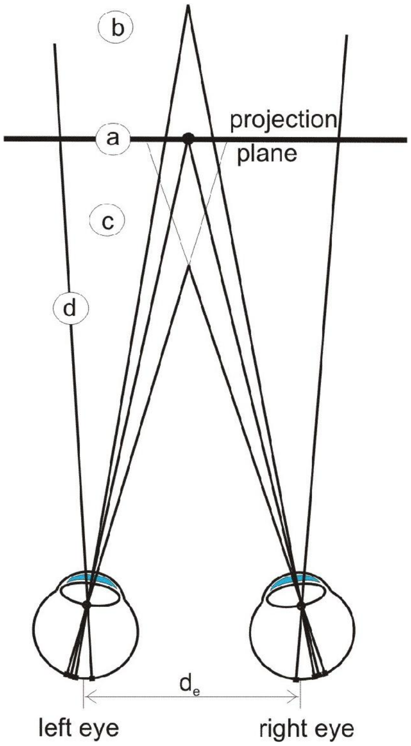


Fig. 3.34 Types of parallax.

2.7 Closed-loop adaptive optics

Accommodation and convergence are closely related to each other when looking at the object in the space. In the real world, accommodation always follows convergence and the convergence point equals to the accommodation point (focus point). The situation is different in the case of state-of-the-art applied stereoscopy.

Human optical system is exposed to unnatural conditions, while looking at a stereo display. We have to keep in focus the display showing us the stereo-images and converge our eyes to fuse the separated images concurrently. So the convergence distance is changing according to the disparity of an object in a stereoscopic image (and the apparent position of the object), while the accommodation is changing just with the position of the observer and projection screen. The projected picture gets blurred if the accommodation is not fixed on the screen. Our eyes conform to these special conditions by maintaining the screen in focus within the value of depth of focus, which is around 0.25 dioptres. This maximum limit is sharpness accepted by our brain, and is changing with the viewing terms in the scene - light conditions significantly affect this value.

It is believed that an inner connection (cross-link) exists between accommodation and vergence mechanisms in our nerve system [19] [20]. As you can see in Fig. 3.35 accommodative and vergence parts of our optical system influence each other through mutual cross-links and feedbacks. A little difference in object and convergence point distances leads in oculomotor system to elimination of resulting disparity by affecting ciliary muscles to put the object into focus. This adjustment process is applied the other way round too. It has been shown that accommodation follows the object in depth, although just within the limits of depth of focus [21]. This follow of the scene motion is restricted by the rapidity. Once the speed of the object in depth exceeds some limits, accommodation response intensity decreases. The convergence stimulus is dominant though, and accommodation just accompanies it.

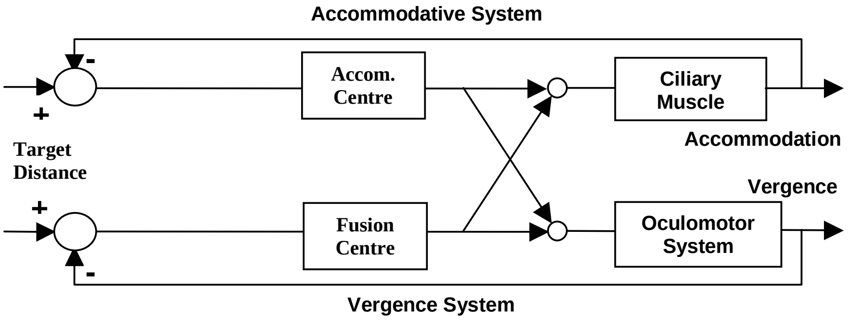


Fig. 3.35 Cross link between accommodation and vergence system.

From the geometrical relationship in the Fig. 3.36 mathematical formula (8) can be deduced for figuring out the proportion of the evoked perception. The change of accommodation by altering the lens shape to bring the object into focus describes equation (9) where the calculated quantity is expressed in terms of dioptres. It follows the formula (10) showing that for certain ΔD value the farther we stay from the screen the greater the spacing of apparent position of the image and the screen is. The change of the apparent image position is valid even for resizing of the projection screen. Image separation $d_e = -d_i$ setting the object distance to the infinity behind the screen is seeable in the computer display with no difficulty, but projecting on the movie theatre projection screen can make the same scene imperceptible, as the optical system is exposed to the conditions compelling eye muscles to diverge the eyes. The larger the display is, the farther apart the two images on the screen, and the more the eyes are diverged. Therefore, the image

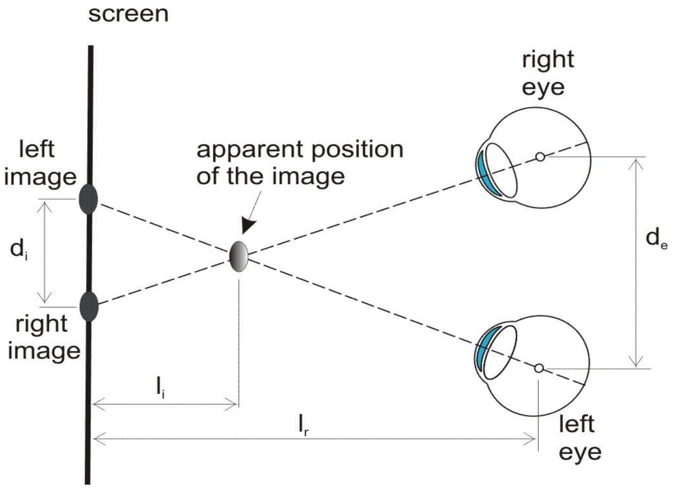


Fig. 3.36 Apparent position of the stereoscopic image. l_r – viewing distance; l_i – apparent object distance from the screen; d_e – interocular distance; d_i – image separation distance

$$l_i = \frac{d_i l_r}{d_e + d_i} \qquad (8)$$

$$\Delta D = \frac{d_i}{d_e l_r} \qquad (9)$$

$$l_i = \frac{\Delta D l_r^2}{1 + \Delta D l_r} \qquad (10)$$

separation of L-R images should not exceed the limit of viewer's interocular distance at all or just within an acceptable limit.

2.8 Optical devices

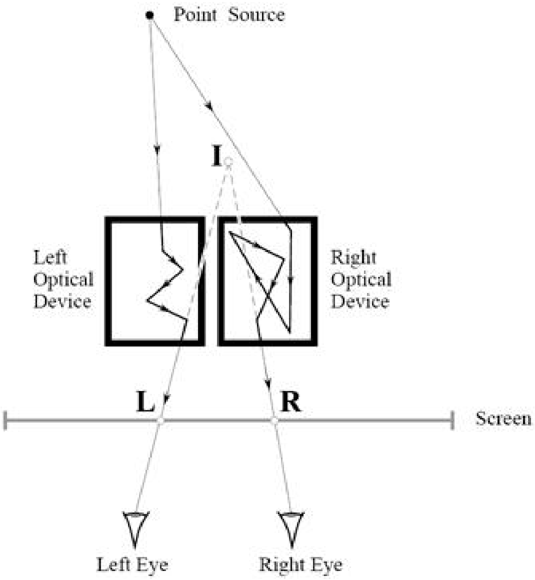


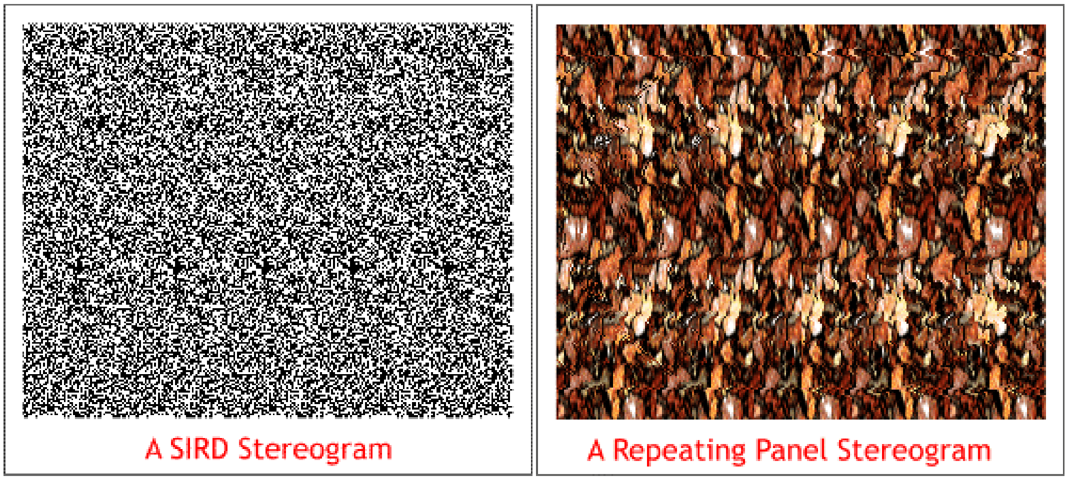
Fig. 3.37 Common binocular optical device (taken from [29])

Despite of the fact that optical devices have gone through a long way of research and technical improvements, there are still an attributes directly influenced by a physical laws. This can cause a radical change in device usage or impairment of its optical qualities. Naturally it is not possible to consider every effect that occurs in optical device. Optical device can be described as a collection of components (lenses and mirrors) controlling the light ray direction. The result is that we see the object where the apparatus makes it to be optically. It is a place where the two rays from each eye intersect (see Fig. 3.37). The images are perceived double in case of absence of the intersection. Many devices providing their user with 3D images make use of such basic optics laws to simulate conditions of watching the real world. [29]

2.8.1 Stereograms

The stereograms are the easiest way to produce 3D perception synthetically. There are many kinds of them, the most well known are called a SIRD (Single Image Random Dots) or a repeating pattern or wallpaper stereogram (see Fig. 3.38). The significant advantage poses the fact that no special device is needed for watching the stereograms. The main drawback is the obvious lag of detail and visual information as a whole.

A simple 3D scenes or objects can be seen in the stereogram if we know how to use it. While looking at something in a real world our eyes converge and focus at the same spot on a surface of an object. Our brain then calculates the distance to the object based on the particular cues taken. But when we look at a stereogram our eyes converge at the plane behind the picture. The images on our retinas are fused correctly thanks to the special construction of these images, which guarantees their overlapping even under such conditions. Our brain interprets this observation as valid (correctly converged and focused) and computes the spatial percept based on the actual cues, even though they are synthetically created. It seems to us that we are not looking at the paper (or display) but that we are looking at something behind the paper instead [22] [25].


A SIRD Stereogram

A Repeating Panel Stereogram

Fig. 3.38 Two basic types of stereograms.(taken from [38])

2.8.2 Colour separation

These glasses, utilizing the colour separation principle, do not change state to provide their wearer with a depth immersion. Specifically created pictures are called *anaglyphs*. No other equipment is needed for this technology to work, only glasses. Placing different colour filters in a pair of glasses has the effect of only letting a particular spectrum of light pass through to each eye. By encoding our stereo image so each image has the colour that is passed by one filter, and blocked by the other, it is possible to provide each eye with different images. These two images are superimposed so one image is a little horizontally shifted from the other. Stereo is finally achieved by letting these images be slightly different according to the position of the vantage points.

The first anaglyph glasses used red and blue filters, but there can also be other combinations depending on the image colour presentation and colour visual output. Red/blue combination is used for greyscale images which are subsequently coded with red and blue colours that are balanced with glasses. These are sometimes called "pure anaglyphs." The problem is that the coloured filters in the glasses can only filter out about

50 percent red or blue (red colour is within the range black to red and equally is blue). So it is not possible to achieve fully contrasting white colour. Therefore, an attempt to get fully contrasting white colour in the anaglyph imagery leads to crosstalk.

The way of seeing fully coloured images is to add third missing colour component (of RGB colour scheme) to the filters. Adding the green colour, which was discarded last time, to the filters helps us to get 'normally' coloured image. There are many possible colour combinations of the filters, but the most frequently used are red/cyan or yellow/blue. Actually, it is possible to use any two colours defining the whole gamut applied in the pictures. But it is good to know that, there will always be a loss of colour information. Different colour filters define different colour palettes. Optimally, the pictures should employ complementary colours to the ones used for filters (or at least on the opposite side of colour cube), since the separation becomes hue balanced. Logically you cannot perceive three-dimensionally complete red image with red/cyan glasses, as the eye using cyan filter will get no visual input.

The main assets of this technology are low prize and ease of usage. Although the main drawbacks, which are significant crosstalk and loss of colour information, outweigh the advantages easily.

The other approach making the use of colour separation is called *ChromaDepth*. The hue corresponds to the depth. The colour is indicating the depth so there is also no possibility of seeing fully coloured images. The glasses employ a special lenses causing chromatic aberration of light. These lenses are of one kind for both eyes and compel the colour components of the passing light to separate (see chapter 2.2.1). Blue colour indicates the farthest part of the scene, whereas the red colour indicates the nearest part. The chromatic information is completely lost, therefore its usage is limited. Particular presentation parameters must thus be taken into account individually.

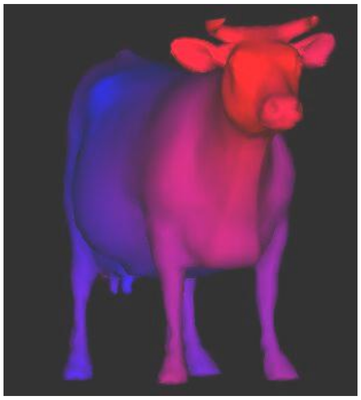


Fig. 3.39 Chromadepth principle

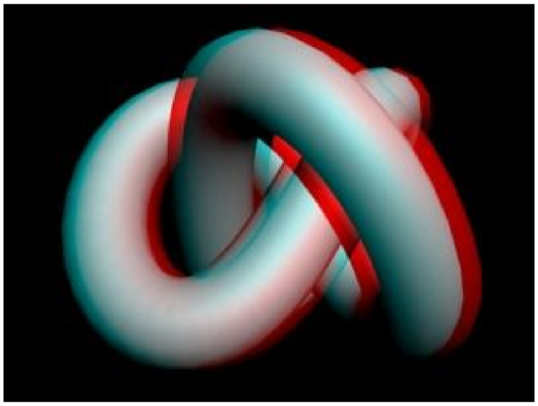


Fig. 3.40 Anaglyph picture for red/cyan glasses.

The *Pulfrich* system bases its stereoscopic effect on a perception anomaly. Darker image is perceived with a delay of several hundredths of a second relative to the brighter image. When an image moves and one eye is covered with filter causing its darkening, the brain concludes (out of the two different horizontal image position) that perceives a true depth. As the movement is the main source of depth information, the camera must keep on moving all the time to provide the depth sensation. Therefore, the main drawback is the specific demand on the image motion [23] [24] [25].

2.8.3 Time-multiplexed stereo images

In contrast to the previous passive glasses, this glasses changes their state according to the actual image on the screen. Systems of this type simply have high-speed electronic shutter in front of each eye, which opens when the correct image is displayed and closes when the image for the opposite eye is displayed, so only one eye sees the display at any time. The liquid crystals are used for the shutters as an electronic signal can make the crystal turn instantly from transparent to opaque.

The biggest problem to be solved is the synchronization of the shutter alternating. If this is not done thoroughly a crosstalk may occur. The communication between graphic card and the glasses is ensured by wires or wireless infrared transmitter (user has to stay within the range of emitter). If the process happens fast enough, user's brain assumes the image of each eye as being continuous. Slower shuttering speed doesn't lead to the loss of stereoscopic perception, but some flickering can be seen, which is usually considered to be a source of strain of our optical system. The usual refreshing frequency is 120Hz. This frequency is a reasonable compromise between an average monitor hardware limits and pleasant visual output.

There is also a drawback in that each left or right eye view is only made up of either the odd or even lines. This results in only half of the screen being used for each image and a 50% decrease in brightness. The more significant drawback is the crosstalk though. One eye sees the image of the other eye for a while because of finite shutter speed or poor synchronization. The best way how to solve this problem is to let the opaque phases overlap each other, which unfortunately results in some flickering and loss of brightness. The most important factor for choosing this technology is a reasonable prize [25].

2.8.4 Head mounted displays

A typical HMD houses two miniature display screens and an optical system that channels the images from the screens to the eyes, thereby, presenting a stereo view of a virtual world. A motion tracker continuously measures the position and orientation of the user's head and allows the image generating computer to adjust the scene representation to the current view. As a result, the viewer can look around and walk through the surrounding virtual environment.

There are two main types of HMD presenting the view of both the virtual environment and the outside world simultaneously: a) Optical see-through HMD – works by placing optical combiners in front of the user’s eyes. Combiners are partially see-through and partially reflective, so user is provided with view of the real world combined with synthetically generated scenes. b) Video see-through HMD **-** works by combining two separate displays and two cameras. Video cameras provide the user with view of the real world. Video from cameras is combined with graphics generated by computer. User has no direct view of the real world. In contrast to the later type, user is “blind” while using this type of HMD when the power is off.

HMDs usually give a large viewing angle offering total immersion in the artificial space, with a possibility of free looking around without loosing the screen contact. The main drawbacks are latencies and tracking errors, which impair the whole sensation.

2.8.5 Light polarization

This technology uses glasses with filters instead of classic lenses. Displaying an effect of spatial cue requires two projectors. Each projector also has a polarized lens over it (polarizers), forming an angle of 90 degrees, like the glasses. "Natural" light emitted by usual light sources is usually not polarized, so all directions of polarisation are randomly and equally distributed. The polarizers basically lines up all the light waves so they are in one orientation. These oriented light waves can only pass through a polarized lens that is polarized at the same angle. The waves in different direction are absorbed, so the overall brightness decreases. If the polarization of the lens is different then it won’t let that light through. A light beam coming from the projector oriented horizontally (for instance) will be seen by one eye, and the light beam coming from the other projector oriented vertically will be seen by the other eye. Hence, you can display a stereo pair of images at the same spot and the viewer will see a single 3D image.

The linear polarization possesses a drawback of the necessity to keep the observer’s head looking perpendicularly to the projection screen with no inclining to either side. A circular polarization solves this problem. The principle is very same as described above except for the fact, that polarizers and glasses filters are changed for the circular ones. One light beam is polarized in clockwise direction and the other in counter clockwise direction [24].

This technology, thanks to the many technical attributes and convincing visual output, represents one of the best solutions for presenting stereo immersion. The only disadvantage could be acquisition and maintenance costs.

2.8.6 Auto-stereoscopic devices

Auto-stereoscopic displays are on the verge of breakthrough these days. They allow user to see its spatial content without using any additional device or viewing aids. On top of that, some of them can also track location and orientation of the user’s head in order to adjust the scene according to the changing viewing angle. Mostly 3D displays are not able to create real spatial image (except for volumetric displays), but they are providing us with separate two-dimensional images, which are consequently blended into one three-dimensional image by our brain. Some basic types of displays and their typical attributes can be seen in Table 1 and 0. The lower the display in Table 1 is listed the more desirable it is for us.

		- Pictorial cue - Motion of pattern	-Binocular disparity - Convergence	- Motion parallax		-Accommodation
				Passive	Active	
2D display		Yes	No	Yes	No	No
3D display	Binocular stereoscopic display	Yes	Yes	Yes	No	No
	Multiple photographic display	Yes	Yes	Yes	Yes	No
	Volumetric display	Yes	Yes	Yes	Yes	Yes

Table 1. Classification of various displays according to their cues for depth (taken from [21])

	Fatigue	Pictorial cue Motion of pattern	Binocular disparity Convergence	Accommodation (active motion parallax)
2D display	No	Yes	No	No
Binocular stereoscopic display	Yes	Yes	Yes	No
Real 3D space	No	Yes	Yes	Yes

Table 2. Difference of cues for depth among 2D displays, binocular stereoscopic displays, and real 3D space. (taken from [21])

There are many kinds of scientific attitudes on the competitive field of auto-stereoscopic displays and so is number of types of devices directly employing them. In the 3D-LCD, using a *lenticular imaging*, a sheet of cylindrical lenses is placed on the top of the LCD in such a way that every subpixel is magnified over the width of particular lens (see Fig. 3.41). A change of the viewing angle corresponds to a shift of the focus point under the lens. Each pixel consists of certain number of subpixels, and thus dictating number of views for different gaze angles. The more subpixels the more realistically the watched scene will appear. This means that 3D display allowing user to see just two different

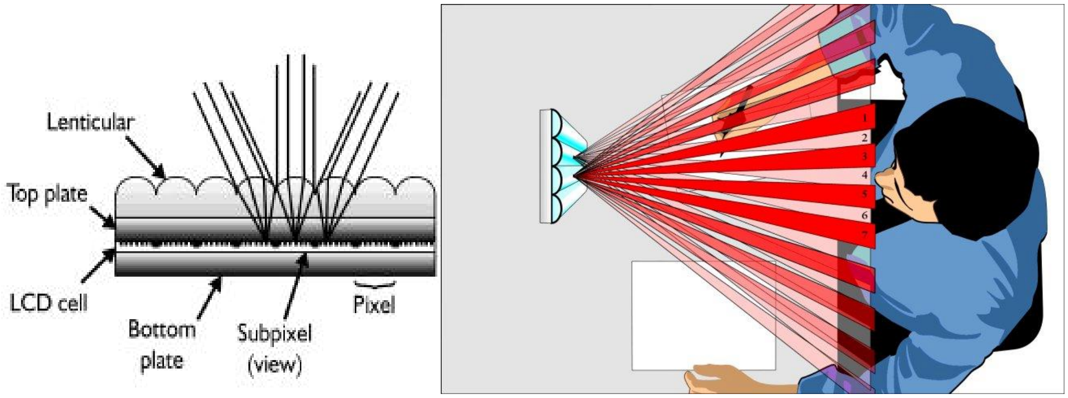


Fig. 3.41 Multiview 3-D LCD (taken from[26])

images each for one eye will have a pixel including two subpixels. This technology makes the usage of the fact that each eye looks at the projection plane at different angle, so for each eye different subpixel can be magnified. Single pixels make up the whole pictures which consequently make up the 3D scene in our brain. Minus for these devices could be quite limited displaying 3D space, and more importantly, narrow area where the user can stay while using one [26].

The most promising so far seem to be the volumetric displays, which generates an authentic 3D image by lighting up the points within a physical substance volume. Created imagery appears to float in volume. These technologies utilize one of the most sophisticated attitudes of all and there are many of them, each one unique. Many researchers believe the future of 3D displays lies with the *static-volume display*, which is a transparent grid of 3D pixels, or voxels. An unlit voxel is invisible, but when turned on, it appears as a spot of light floating in space. It uses a block of transparent glass, gas or liquid, in which voxels are illuminated by intersecting two invisible infra-red laser beams. To create a complete image, the lasers are scanned throughout the physical volume, to repeatedly light up all the corresponding voxels, often enough to maintain a stable image. Volumetric displays offer best solution for presenting 3D world, but the drawbacks could be the limited displaying range or enormous prize [27].

3 Stereoscopy parameters

3.1 Correct stereo scene

3.1.1 Camera’s convergence

Most people starting with stereo-images creating think that the cameras should converge on the point of interest in the sampled scene in the same way as our eyes in reality do. Although as a consequence specific visual discrepancies emerge. A negative side effect has an impact on any 3D scene but evident picture perception degradation (also known as *keystoning error*) occurs especially when close-look pictures are taken. The best way how to show the effect of keystoning error is giving an example. Imagine evenly spaced lines on the wall making a grid model. Take two identical aberration-free cameras with parallel axes pointing perpendicularly at the wall and take the pictures. You will get perfectly symmetrical pictures of the grid with all the lines perpendicular. But taking the pictures with the cameras converged on the object cameras will lead to a different outcome. Particular images taken under such circumstances show apparent geometrical errors. The grid is not even nor are the lines perpendicular. The whole shape is squeezed on one side. These shapes are called “keystones”. If the one tries to fuse these images with our eyes an unpleasant feeling may occur or even a pain. In any case the vertical disparities, created this way, cause unnatural 3D perception of the scanned scene provided it exceeds a value 3 min of arc.

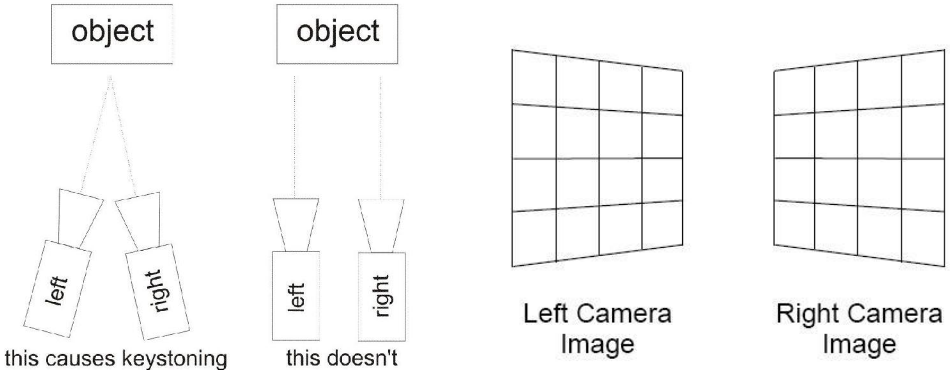


Fig. 3.1 Keystoning error source. (right picture taken from [30])

The only way how to get geometrically correct images is to let the cameras’ axes to be parallel. The whole scene is then displayed as placed in infinite negative parallax and to make the scene perceptible a little post-processing of the images is needed. It is necessary to put the object of interest in zero parallax. Horizontal image shifting is the way how to do it. The object is in the zero parallax when the two images of it completely overlap.

3.1.2 Microstereopsis

The relation between the level of disparity and the user’s ease of fusion is inversely proportional. The further apart (for constant distance) two images of 3D object are, the harder it is for a viewer to percept a single imagery. In an extreme the stereo-object can become imperceptible for us thus making double-vision and eye strain. There have been conducted an experiments showing that disparities equal to just few percent of interocular distance is sufficient to produce binocular stereopsis and above that it produced less visual discomfort for users while watching the scene. This paradigm is called *microstereopsis*. [31]

To stimulate the depth perception over the range of a whole scene we need to use enough cues (see chapter 2.5.1) intensifying the depth information in the image. The main idea of microstereopsis is embraced in the following six points (following six points are cited from [31]):

1) If a scene contains enough familiar detail that its depth structure can be deduced by high-level reasoning, then adequate binocular stereopsis can be stimulated by perspective disparity that is substantially smaller than the disparity demanded by the “geometrical correctness”.
2) Smaller-than-“correct” disparities stimulate smaller-than-“typical” portions of the physical and mental discomforts attributable to conflicts between depth sensing modalities.
3) Disparity reduction by left/right shift of the members of a stereo pair to make the disparity around the center-of-interest approximately zero is effective.
4) Disparity reduction by reducing the interocular separation to a value smaller than the human interocular separation (which is the required camera separation for geometrical correctness) is also effective.
5) Left/right shift and reduced interocular separation are synergistic: they are especially effective in combination.
6) The combination of reduced interocular separation and other depth perception stimulating factors, especially perspective distortion, and motion parallax are also complementary.

Binocular stereoscopy induced this way is distinguished by disparity coming through a slight blurring in the foreground and background of the scene. The scene without eyewear is discernable without any problems and after putting on a eyewear the spatial percept occurs immediately.

3.1.3 Correct depth perception

Unnatural depth cues provided by 3D displays may cause fatigue and diplopia. Useful technique is to apply rendering which employ smaller interpupilar distance than actually is. But this attitude makes the observer to perceive the depth incorrectly and this could be a problem in such applications where this feature is crucial (e.g. industrial design). This problem occurs especially when the displayed object is positioned in front of the projection screen. Method for improving accuracy of depth perception has been proposed in study [40].

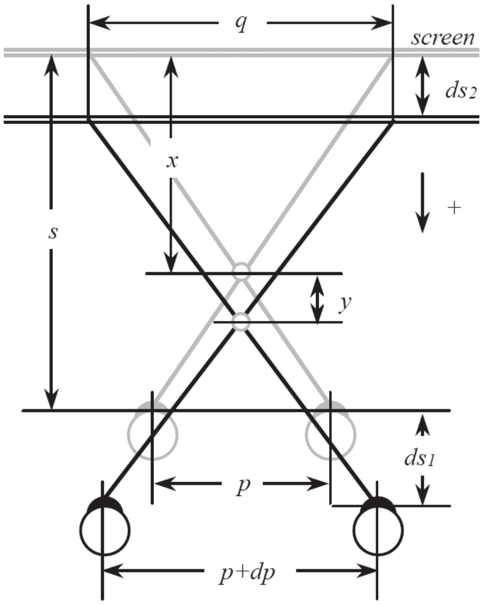


Fig. 3.2 Arrangement of the parameters for the modification.(taken from [40])

In the Fig. 3.2 we can see grey lines denoting the rendered scene before correction, the black ones denoting the scene after the correction. There have been proposed three main parameters in the paper influencing the depth difference significantly: p…interocular distance, s…distance between the eyes position and the screen, x…distance between the apparent object position and the screen. Parameters *dp*, *ds1* and *ds2* modify these distances to the optimal ones.

The following equations are gained from the Fig. 3.2:

(11) $$\frac{p}{q} = \frac{s-x}{x}$$ (12) $$\frac{p+dp}{q} = \frac{ds1+s-x-y}{x+y-ds2}$$

And after some adjustment steps we get:

(13) $$y = \frac{px(ds1+s-x)-(s-x)(p+dp)(x-ds2)}{(s-x)(p+dp)+px}$$

For more information about this correction technique see [40].

Correct depth perception is fundamental for every stereo images creator who wants to get precise and predictable three-dimensional immersion. Knowing the size of the projection screen and the distance from (S) it the one can calculate exact reproduced position D. This fact is given by basic geometrical law expressed by formula (14) where *I* is interpupilar distance.[46] This function is only theoretical, though, not taking into account physical constraints of the human visual system so diplopia and eye strain may occur.

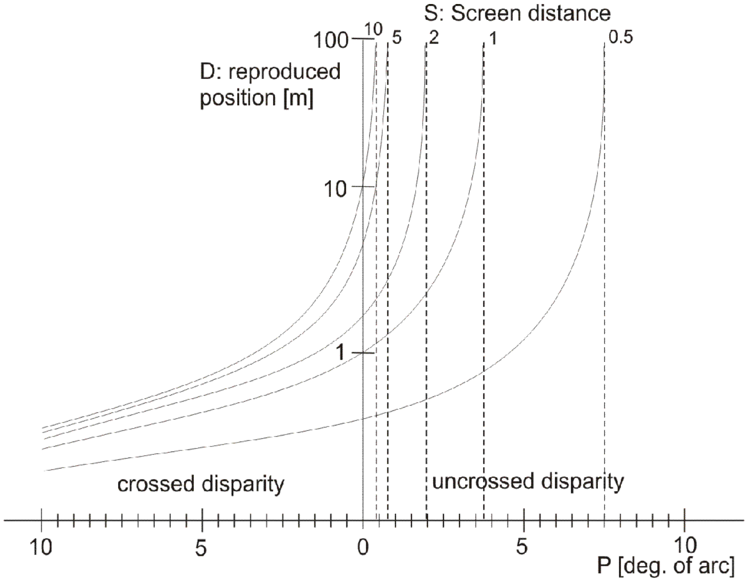


Fig. 3.3 Reproduced position (D) of stereoscopic image as function of binocular disparity (P) at various screen distance (S)

$$(14)\quad D = \frac{1}{\frac{1}{S} - \frac{P}{I}} = \frac{S}{\left(1 - \frac{E}{I}\right)}$$

3.2 Viewing conditions

Not just the parameters of presented stereo scene directly influence the gained perception but even the outer conditions do. Actually all the questions concerning viewing conditions haven’t been satisfactorily answered yet and many of them need rigorous examination. [32] [33]

3.2.1 Screen size

The screen size is a significant parameter affecting the whole viewing impression. Basically the more of our field of view (both horizontal and vertical) is taken up by screen the better, as the screen edges are often a distracting factors. Especially, bright scene edges with abundant movement considerably stimulate peripheral eye receptors and thus distract viewer from the action in the centre. The angle subtending the screen proportionally changes with the size and distance. It also has direct bearing on the required resolution of the image and the technology used for delivering the imagery. Even the inter-camera distance and focal length have to be adjusted to screen measures and viewing distance, otherwise distortions could occur in the depth reproduction.

Some irritations may also appear when the size of the displayed object (changing with the size of the screen) doesn’t correspond to the familiar size of the real object. Object in normal viewing is always perceived as being constant in size regardless the distance and visual angle it subtends. Reproduced object may appear smaller or bigger irrespective of our former experience. The collision of distance and angular size with object size is possible to solve by changing the object parallax accordingly. Generally larger screens are more suitable for 3D viewing as they fill up more of our field of view, the object size reduction doesn’t have to be as substantial and the overall psychological and visual impression is rather more persuasive. The aspect ratio is proposed to be optimal from 3:5 to 3:6. The minimum size of a stereoscopic display hasn’t been proposed yet.

3.2.2 Viewing distance

Optimal viewing distance depends on a screen size and picture resolution. For the given screen size, the closer you stay to the screen the higher image resolution you need to maintain correct visual information. The quality is linearly dependent on the logarithm of the viewing angle. The optimal distance for images with limited resolution is determined by the visual cut-off frequency at the screen of value 16 cycles per degree. Movement is another attribute affecting optimal viewing distance. It is better for the viewer to stand further away from the screen in case of ample motion content, as the inadequate distance can lead to an eye strain. The distance is commonly proposed to be optimal about three times the height of the screen and the picture pick-up should be optimized for it. The perceived relative depth of the 3D object is directly proportional to the distance from displaying apparatus (see chapter 3.1.3).

3.2.3 Accommodation distance

The accommodation is linked with convergence as described in chapter 2.7. Since the objects appear sharp only in the plane of displaying, the user of both 2D and 3D display is compelled to focus to a fixed distance. It is not a problem in case of 2D displaying but when it comes to 3D problems may arise. As described earlier, accommodation in a real vision always follows convergence. When the object becomes out of depth of focus it turns blurred, which helps us to repress the effect of double vision. But it cannot be done this way in case of 3D imaging, so when the disparity exceeds limit of the depth of focus of the observer’s eyes, the accommodation is suppressed regardless the convergence angle. It has been proved, that this is the main source of stressing the visual system, as our eyes are exposed to the conditions very different from the common ones. [21] The convergence and accommodation jointly contribute to the perception of depth as described in chapter 2.5.2.

3.2.4 Disparity range

The threshold of the lowest distinguishable angular disparity is about 2 seconds of arc (but may be coarser up to about 0.8 min of arc). To reach this limit we need a display capable of picturing a horizontal spatial disparity of at least 24 cycles per degree. The perceptible upper level of disparity is dependent on the time the observer is exposed to the image stimuli. The largest disparity at which fusion occurs is called the disparity limit of fusion. The disparity limit of fusion changes directly with the stimulus size or scale and inversely with spatial frequency (i.e. large disparities can be fused only with large low-frequency stimuli). Average threshold for the presentation period of 200 ms is 27 min of arc for crossed and 24 min of arc for uncrossed disparity. For 2 seconds of presentation period, the disparity thresholds reach significantly larger values to be brought within the fusion range. Particular values are 4.9 deg of arc for crossed and 1.6 deg of arc for uncrossed disparities. Large disparities, though, may cause increased visual strain and fatigue.

3.2.5 Motion parallax reproduction

Motion parallax is one of the monocular cues helping the observer to distinguish the depth in the picture. According to the principles of linear perspective, objects in depth are affected more than objects in the zero parallax plane. Thus restricting the depth of the scene can suppress the effect of this cue. The motion parallax is continuous in a real vision of world and convincing presentation of this phenomenon for more observers simultaneously is one of the biggest challenges in the technology of 3D displays.

Common technologies for reproducing stereoscopy offer one fixed viewpoint of the user. Changing observer’s position leads to an unnatural moving and skewing of the objects. It is caused by fixed images which do not adapt to the different viewing angle (see Fig. 3.4). The brain interprets the situation in the same way as the correct scene and thus resulting in distorted 3D image. Points in the apparent position in front of the screen move with the user whereas points behind the screen they move in opposite direction. The solution could pose head tracking systems adjusting a scene instantly or multi-view displays with a limited set of views (see chapter 2.8.4 and 2.8.6) providing discrete viewing-angle-dependent changes. There were experiments examining the motion parallax on multi-view systems concluding that the threshold for motion parallax quantization step is 1 min of arc. That means, if you want a scene with 20 min of arc of smooth motion parallax, you will need 20 different binocular image pairs. Naturally, methods for interpolation the adjacent views exist, but yet they need some more investigation in this field.

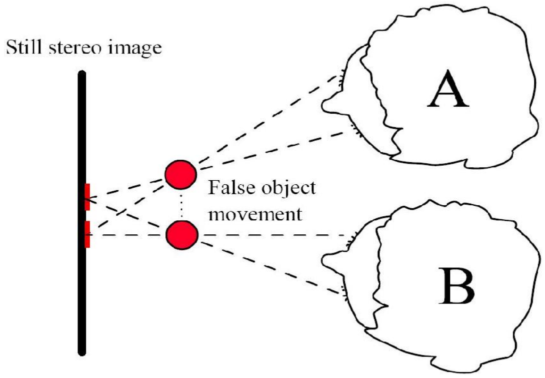


Fig. 3.4 Motion parallax distortion while moving from position A to position B. (taken from [34])

3.2.6 Picture quality

Not just a geometrical symmetry is important for the correct perception of the scene but also a symmetry more closely related to the technical aspect of the 3D presentation. The picture quality could embrace temporal asymmetry of image presentation, noise interference, and luminance and chrominance asymmetry. [32]

Temporal asymmetry of an image presentation means an asynchronous projection of particular images. This doesn’t represent any noticeable problem as long as the delay between the left and right images doesn’t exceed 50 ms. This assertion also defines the minimum frequency for an alternating manner of image displaying along with the greatest stereo depth which is possible to perceive. It is equal to 65 min of arc at 120 Hz, 50 min of arc at 60 Hz and 10 min of arc at 30 Hz. Flickering is insensible when about 55 or more images per second are presented to each eye.

Dynamic visual noise interference is the basic problem for 3DTV broadcasting. It manifests in the image degradation thanks to a technical imperfection of particular steps from picking up to displaying to the viewer. The deterioration of 3D percept is closely connected to the level of noise presence.

Luminance asymmetry doesn’t significantly influence the stereo immersion until the difference exceeds about 6 dB for stationary and 0.2dB for scenes with a movement. Such a difference between these limiting values is caused by the Pulrich effect (see chapter 2.8.2), which uses the luminance difference for presenting the depth sensation.

Chrominance asymmetry is not a disturbing element as long as the difference in wavelength is less than 10-100 nm. In case of not meeting this condition a binocular rivalry may occur. [15]

4 Visual strain and fatigue

A lot of work and research has already been done to make the perception of reproduced stereo-world closer to the reality. Up to now there is no perfect method for providing faultless 3D stimuli to human senses. The correct immersion is affected by many factors starting with the parameters of the scanning apparatus, going through the viewing conditions, and ending with the attributes of the image presenting device. Each of these imperfections more or less contributes to an unnatural visual environment influencing negatively our optical system. Rules for creating 3D stereo immersion are quite strict and any infringing can lead to an incorrect or ambiguous percept, strain and fatigue of our optical system, or even cause a sickness and pain.

Naturally this problem has been examined from every possible point of view by many competent people all over the world ever since the first pair of stereo pictures has been created. This part of the thesis will cover such papers and analyse their outcomes and observations.

4.1 Main causes

Basically any imperfection in the whole set of elements included in a stereo imagery presentation creating conditions different from the real ones may cause some kind of distortion. Even the most insignificant ones can lead to a considerable negative affection.

Here is a list of the main visual stress contributors:

a) Breakdown of the accommodation & convergence relationship – see chapter 4.2
b) High values of the parallax – see chapter 4.3
c) Crosstalk (=ghosts) – occurs when picture dedicated to the left eye view partly shows up in the right eye view and vice versa. It is very common for technologies based on colour separation, light polarization, where the main problem reside in insufficient filtering and also in time multiplexed glasses caused by bad synchronization of displayed images and shutters. There was found 50 ms to be a limit for the delay of presented image pair [32]. This also significantly decreases fusional limits [46].

d) Conflict between interposition and parallax cue – screen surround cuts off or touches an object in a viewer space (space between the viewer and the screen). This is substantial image cue conflict. The negative parallax in the image says that object is in front of the screen whereas interposition of the screen edge and the object says right the opposite thing. This phenomenon usually leads to an ambiguous depth perception, and spatial confusion of the viewer. [37], [45], [47]

e) Technical imperfection and setting of the 3D apparatus – different brightness of the images, colour, contrast, flickering occurrence. Basically all the aspects regarding settings and calibration of the stereoscopic device or auxiliary optical apparatus (glasses). [32], [48]

f) Expanded (infinite) depth of field – describes the situation when depth of focus of an observed scene is wider than it actually is in reality. The viewer sees then double-vision of "ungazed" objects sharp which is in direct contradiction to the real world where every object blurred proportionally to the distance of the gazed point. The higher is the disparity difference of examined objects the higher is the negative impact on the viewer. It leads to excessive disparity information. [21],[44]

g) Vertical disparities – caused by convergence of the cameras and faulty calibration of the 3D presentation apparatus (different focal lengths of the camera lenses). This problem is one of the worst as our optical system has very restricted means to deal with it in any way. [30]

h) Common cues collision – any logical collision of both the monocular or binocular cues presented in chapter 2.5.

i) Sudden changes in the depth of the scene – the continuous motion has been proved to be much more comfortable for viewer than abrupt discrete changes. It is good to take this fact into account in the editing of 3D movies, by reasonable application of film cuts [32]. [21]

j) Excessive motion content – any motion contributes to the excessive strain of our eye either in 3D or 2D movies. [39], [42]

k) Viewing conditions – this includes such conditions like viewing distance, screen size, lighting of the room, viewing angle etc. [32], [33]

l) Geometrical distortions between left and right images - Pastoor describes geometrical distortion through decreasing geometrical acuity as a possibility of visual strain source in case of viewing over a longer period of time [32]. [42]

m) Differences between the electrical characteristics of the left and right images – very specific and kind of a minor problem described in [42].

n) Low brightness of the images – setting the brightness as high as possible is the easiest way how to make the viewing of stereo pictures more comfortable, as the pupil contract and thus increase the depth of focus of the eye. [19], [21]

o) State of health of the viewer – there are many diseases and disabilities making the observer unable to perceive depth correctly.

p) Duration – well computed scenes are more likely to be perceived without any problem for a long period of time. On the contrary, negative influence commonly affects human optical system faster during a defective scenes observation.

4.2 Breakdown of the accommodation & convergence relationship

Breakdown of the accommodation & convergence relation is the most common and frequent cause of the visual stress which is basically mentioned in every study dealing with stereoscopy in any way. In the real world the accommodation and convergence coincide with each other within very narrow limits. The artificial conditions of the state of the art stereoscopic presentation device mostly offer fixed focus plane which the one has to focus on to see stereo images sharp. Disparities in the stereo scene more or less make the objects come out of this plane thus causing unnatural visual environment for our visual system. The experiments showed that practice is a good way how to get used to the minor discrepancies.

Study [39] examines this problem through measuring the subjective degree of visual fatigue from the change of accommodation response before and after viewing stereo images. They found, that our visual functions return to normal in about 30 min after an exposure to such unnatural conditions. The experiment was based on viewing scenes for a particular time span. The accommodation response was measured by a special optometric device. The eyes were exposed to a stereoscopic stimulation where a displayed object step-changed his position in depth from -0.16 diopter to 5.10 diopter. The responses varied with every subject. Yet the results demonstrated clear more or less suppressing tendency in accommodation waveform measured after the viewing. The change of accommodation response waveform corresponds to the estimation of visual fatigue. Some subject may have felt an eye strain whereas other subject under the same conditions may have not. However, direct transformation of accommodation response to the visual fatigue evaluation was found not to be possible and thorough examination is necessary to determine which physical values should be included in the transformation. Rather the same impact on the eye accommodation functioning had the watching of the 3D movie. In order to find relation between the visual discomfort and caused visual fatigue, they proposed another experiment incorporating watching two test movies of 15 and 10 minutes duration. In addition, they evaluated a viewing comfort by subjective impression while watching the sequences in the scale from 5 (no discomfort) to 1 (intense discomfort) – so called single stimulus quality evaluation (SSCQE) [41]. The results indicated that the scenes causing a visual discomfort generally contained objects between the observer and the screen and moved rapidly.

The discrepancy between accommodation and convergence occurs when objects come out of the screen out of the depth limit set by the depth of focus of the human visual system (ranges from about -0.2D to 0.2D). When the stereoscopic images are displayed within the depth of field, it has been shown that the gaze point and focus point are at the same position [43]. Physical distance in front of or behind the screen is dependent on the viewing distance of the observer from the projection screen. In the study [39] viewing distance of 4.5 m was proposed to get the field of comfort to “reasonable” limits of 2.38 to 50 meters. Whereas decreasing the distance to 100 cm reduces the limits of depth of focus to the range of 83.3 to 125 cm from the user. As the movie sequences evoked the visual strain even if all the scene objects were within the limits of depth of focus, it has been concluded that the comfort deterioration had to be brought also by some other intervention than just by a conflict of accommodation response and convergence eye movement in that experiment.

Subsequent study ([42]) of a party of scientists further develops the ideas included in the previous work described above. Apart from accommodation/convergence conflict the main source of visual strain has been given excessive binocular parallax (see chapter 4.3). They pointed out the role of so called Donder’s line expressing the coincidence of convergence and accommodation in the real viewing conditions. They also mentioned the Percival’s area which was derived from Donder’s line, defining visual comfort area in the range of 3D on both sides of the display screen. According to the results of some experiments the range of viewing comfort has been defined as being from 0.67 to 1 degree which doesn’t differ greatly from the results of ±0.82D obtained from calculations based on the range of depth of focus. They concluded that viewing the point within the depth of focus doesn't eliminate the eye strain but only decreases the possibility of stress occurrence by providing more "pleasant viewing conditions". This time authors proposed an experiment of reading stereo texts for four times 15 minutes with 3 minute breaks at different apparent positions in the depth. After the reading the subjective evaluation SSCQE was carried out. It has been shown that motion content significantly affects the visual comfort.

The same source of the visual stress (accommodation/convergence conflict) was termed in the study [21], although another one was also proposed concurrently in the first time. The issue was the situation when two objects with a large disparity are seen in a real world one of them becomes blurred, whereas both of the objects are in focus with stereoscopic display thus providing us with excessive disparity. This problem thanks to an experiment performed (displaying images containing the disparity or not) was found to be unfounded in terms of fatigue. On the other hand, this party designed a special optical device making wider the depth of field through an aperture stop (see chapter 2.2.5). User watching a stereoscopic scene on the display sees an image always in focus regardless of the change in accommodation. It has been found this way that accommodation in this case precisely followed convergence. The change of accommodation was induced by the change of convergence. The results showed that accommodation followed sinusoidally moving object in depth exactly when the frequency did not exceed 0.3 Hz. This outcome validated the assertion from chapter 2.7. The problem of accommodation & convergence discrepancy can be quite reliably removed thanks to this apparatus. They compared the fatigue evoked by watching a stereo display with and without the aperture stop. The subjects jointly determined the visual fatigue less noticeable with the aperture than without it. However, some of them differed in their opinions. The authors assigned this result to the situations when an object moved away from the axis in the centre of the viewpoint and became partially covered with the aperture. For that reason an auxiliary optical device have to be developed to suppress this drawback. The images also became less bright while using an aperture, so the display brightness was recommended to be set as high as possible.

Rather the same conclusion presented Mr. Hiruma and Fukuda [21]. According to their experiments, increasing display brightness is one of the easiest ways how to make the stereo scene more comfortable for viewing. They also remarked that strain could be experienced even during 2D screen viewing, for instance, if the scene contains objects changing their size substantially and rapidly. They proved the idea of closed loop optics between accommodation and convergence through measuring by infra-red optometer, showed that accommodation is suppressed when it exceeds depth of focus range and put forward the advice for securing high-quality stereoscopic sensation to stay always sufficiently far away from the projection screen.

Pastoor in his study [32] suggests compressing the depth range of the scene to the limits defined by the depth of focus, which leads to less intensive 3D sensation but on the other hand substantially reduces bad experiences from a stereoscopic apparatus.

Mr. Perring with his group termed accommodation & convergence conflict and expanded depth of field (problem with infinite depth of field in artificially created stereo scenes) as main causes of visual strain [44]. They defined visual comfort function C (see Fig. 4.1) that depends on spatial frequency (see chapter 2.2.4). Visual comfort was evaluated in a range of five discrete figures from ‘very annoying’ to ‘imperceptible’ (i.e. no visual stress). There has been set a comfort condition which restricted the waveform by a threshold value thus creating a comfort area in C - in this case between ‘slightly annoying’ and ‘perceptible, not annoying’. They applied three different algorithms (using C function) to meet the comfort condition through masking “problematic” regions. The algorithm ‘The Virtual Curtain’ grayed the points difficult to for fusion. The second algorithm ‘The Virtual Pane’ replaced particular regions with smoothed version of the original image. The last in this roll was ‘The Adaptive Haze’ which controlled directly the spatial frequency of the image. So the regions with high frequencies were adaptively hazed. To examine the impacts on the visual comfort after employing these algorithms the authors conducted an experiment in a form of game. The player saw a wire going through the scene and the task was not to touch it with the freely movable loop the user operated. The scene was also enriched with simple objects positioned randomly within the range of depth. Three kinds of data were collected: 1) numerical data -errors in the disparity, 2) verbal reports – subjective evaluation of the particular filters, 3) qualitative data – evaluation of the game in terms of visual strain. The results showed that the most persuasive eye strain reduction provided the algorithm ‘The adaptive Haze’, using a truncated wavelet reconstruction. However, none of the attitudes significantly improved the performances of the participated subjects, which was mainly blamed on the lower rate of the image reproduction.

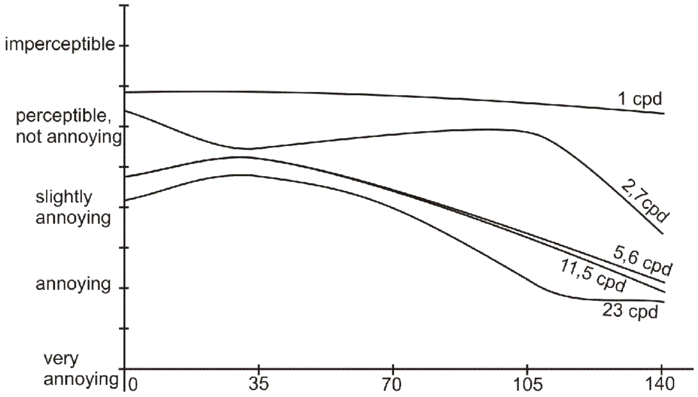


Fig. 4.1 Visual comfort function. Verbal rating as a function of disparity (in min of arc) and spatial frequency.

4.3 High values of the parallax

Parallax results in disparity on the eye retinas. If the values of disparity are too high, oculomotor muscles are compelled to converge the eyes into unnatural positions, thus causing uncomfortable viewing situation. More specifically, it has been found that worse negative impact have the negative parallaxes (crossed disparity) than the positive ones (uncrossed disparity).

Mr. McVeigh, Siegel and Jordan proposed in their study [37] a method which automatically reduces the parallaxes through shifting all the objects to lie on, or behind the projection screen. Each point in the scene is mapped to the corresponding points p_r and p_l in the right and left images. The physical separation (disparity) of these two points defines fixed position of the point in the space. The relation between the point's screen disparity and its perceived depth is described by formula (8). It is possible to change this position in depth correctly by horizontal shifting of the images and subsequent cropping. Assuming that we know the disparity of the closest object in the scene, we can move these points to lie over each other, thus making the corresponding object to be placed in the depth of the screen (see Fig. 4.2). The disparity of all points in the image will be translated by this amount, and the depth proportionally to it (the depth filed of the scene becomes lengthen). The entire scene placed behind the closest object lies behind the plane of projection. Overlapping parts of the image have to be cropped accordingly. This procedure also works even if the closest point lies behind the screen already (positive parallax), just the image translation is performed in the opposite direction. Not only we can suppress adverse impact of the extreme parallaxes on our eyes, but also we completely solve the problem with conflict between interposition and disparity depth cues.

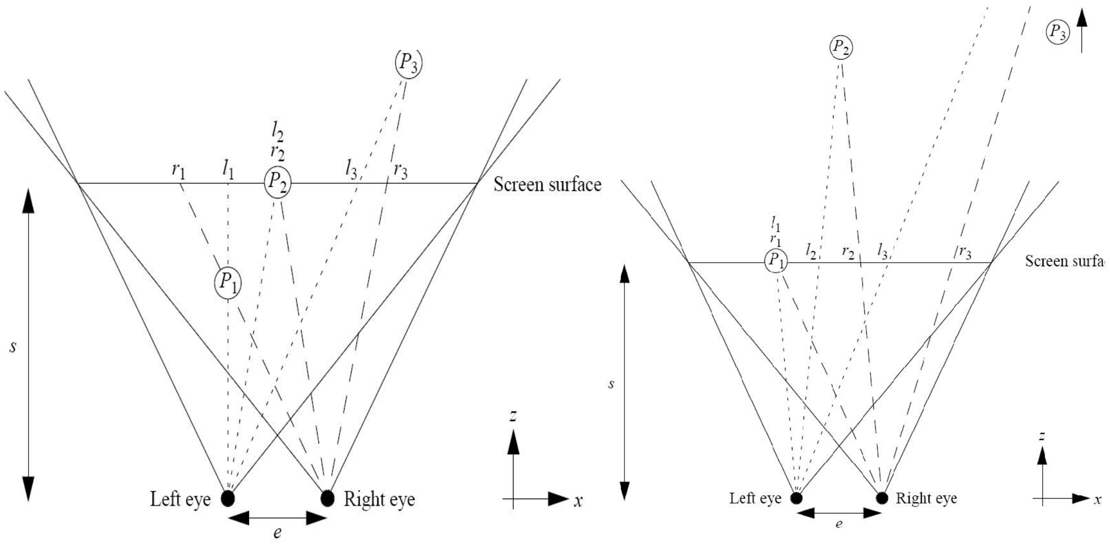


Fig. 4.2 Relation between disparity and perceived depth: (left) before algorithm application, (right) after algorithm application. (taken from[37])

$$\hat{d}(x_r, y_r) = \underset{\hat{d}(x_r, y_r) \in R}{\arg\min} \left\{ D\left[rblock(x_r, y_r), lblock\left(x_r - \hat{d}(x_r, y_r), y_r\right)\right]\right\} \tag{15}$$

The biggest issue here appeared to be the disparity estimation though. Due to the parallel camera configuration the disparities are considered to be only in horizontal direction. We are to go through the image stereo-pair and find the disparity of the closest point to the viewer. As the experiment dealt with moving scenes, some form of block-based displacement estimation was employed. Its task is to find the relative location of the given block in the reference frame that minimizes a distortion function. Position of each block in the frame is compared with the position of the corresponding block (within the horizontal search range R) in the reference frame (prediction of the right-eye image from the left-eye image) and the outcome of a given distortion function (15) is the estimated disparity value, where $rblock(p_r)$ and $lblock(p_r)$ are the right and left image blocks, D[*rblock, lblock*] is the distortion between the two blocks, and $\hat{d}(x_r, y_r)$ is estimated disparity value. Common distortion functions are the mean-squared error and mean absolute difference between the luminance components of the two blocks. If it weren't for the calculation errors, the disparity range acquisition would be trivial. The actual value of disparity range can be found using the statistical model developed by the authors. An estimate of the actual disparity range is obtained by thresholding the disparity histogram to avoid the contribution of false disparity values. From the histogram they obtained the probability density function of the actual disparity values, which yielded the desired disparity range.

Another study for controlling a disparity in the scene based on new algorithm was developed thanks to the party of scientists from University of New Brunswick [45]. The algorithm dynamically sets the eye separation during the movement across the computer generated scene. It is clear that if we set the distance of the eyes to zero, binocular disparity is lost and we get a flat picture, whereas if we set the distance more than the actual we will get scene looking deeper. First the authors put forward a concept of effective eye separation. Observers were to set the eye separation which was comfortable for their viewing of the scene picturing a plane covered with objects moving from behind to the viewer. The angle of the plane subtended to the viewer varied from 0 to 90 degrees of arc. A statistical model has been created according to the gained values. The algorithm itself consisted of three separate stages: 1) Determining the depth of the objects in the scene by going through Z-buffer. 2) Cyclopean scale – first the nearest point in the scene is found and then the whole scene is moved and scaled about a point positioned just between the two eyes in such a way that the projected image stayed unchanged. But the depth of the scene was intensified and the nearest object was positioned just behind the screen after this step. 3) Adjustment of eye separation – this part was dealing with the usage of EES described earlier. Objects are positioned behind the screen, the final step is to change the distance of the eyes in accordance with the EES function with depth as a parameter. For particular mathematical background see [45]. This algorithm reduces vergence-focus conflict, high values of parallax/disparity and collision of an object and edge of the screen. The authors through this study emphasized the superiority of the kinetic depth and linear perspective cues against the stereoscopic depth cues.

4.4 Fusional limits

Binocular fusion of images on our retinas produced by watching a real world is normally carried out without any substantial effort. While watching artificially created stereo scenes unnatural conditions may occur and a visual strain caused thereby. The fusional limits are directly influenced by quantities like time, space, brightness or colour. The higher the values the higher the fusional limits will be. Mr. Nagata performed a couple of experiments examining such conditions [46]. First was an experiment of measuring fusional limits at different distances. There were used stereoscopic images of random rectangles, on the apparatus allowing user to set parallax and position of the pictures. The interesting outcome was that the subjects experienced with stereoscopic pictures had, on average, higher fusional range. Another finding was that disparity limits of objects in front of the screen were higher that of the objects behind the screen. Second experiment dealt with measuring for various fields of view at fixed viewing distance. The subjects were provided with several colour ovals with various binocular disparities and different lateral lengths. In both cases the findings indicated that fusional limits increased with increasing field of view angle (advantage of HDTV displays). Third experiment examined the influence of surrounding images on target. The subjects in this case were asked to watch scene with colour rectangles and white zero-disparity rectangle in the middle. The results showed clear tendency of increasing fusional limits with increasing viewed target size. However the author claims that the increasing range isn’t directly the result of the increase of target size but the decrease in its surrounding area. Also blurred and uniform target surroundings increase the fusional range and slightly decrease it a dark surroundings. Visual fatigue and stress is a possible consequence of images the viewer is unable to fuse. A high fusional limit means smoother binocular fusion with less fatigue experienced by the viewer.

5 Practical experiments

This ample theoretical information load is quite convincing thanks to the hard and meticulous work of many research workers, professors, students or enthusiasts. Nevertheless there are countless questions which need to be answered and doubts which need to be clarified. Even though this work is focused more on the theoretical part of the problem, it was inevitable to make lots of practical experiments addressed to the particular issues encountered during my studies, most of which were carried out on human subjects subjectively evaluating projected scenes.

5.1 Particular work

Till this time there hasn't been proposed a method empirically measuring an impact of artificial 3D scenes on human organism. There were some but the essence of most researches is a 'subjective evaluation' approach. This is because of differentiated and non-exact human perception of either real or fake stereoscopic scene. Different subject commonly means different scene perception and different both positive and negative effects. Subjective evaluation supported by basic statistics is the approach I used in my work.

Accomplished principal experiments:

- questioning visitors of IMAX cinema
- static pictures projected on university stereoscopic apparatus
- movies projected on university stereoscopic apparatus
- anaglyphs projected on CRT screen
- anaglyphs projected on miniature mobile LCD screen

5.2 Technical background

5.2.1 IMAX cinema

The ground of IMAX is about forty years old (EXPO 67) applying the principle of light polarization – polarized glasses (see 2.8.5), possibly a headset that includes electronic liquid-crystal shutter (see 2.8.3), with special video and sound devices capable of creating and reproducing an immersive surroundings on a large scale (special cameras, 70 mm film, powerful projectors, surround sound etc.). There are two kinds of IMAX at the moment: IMAX 3D and IMAX Dome (see Fig. 5.1). IMAX 3D with a flat screen, perpendicular to the cinema floor and seats placed on a ramp inclined in 25º. Projectors are located behind the visitors opposite to the screen. IMAX Dome uses a semi-spherical screen placed above heads of visitors. Seats ramp is inclined in 30º. Projector is placed in the middle of the ramp using fish-eye lenses to cover the whole screen over. This solution specially designed to the edge of peripheral vision both laterally and vertically is greatly emphasizing sense of involvement thanks to the suppression of adverse effects of foreign objects in the visual field of the observer.

To complete the immersion of the IMAX surround sound system, the IMAX flat screen is perforated with thousands of tiny holes to allow the sound to flow through freely. Nowadays, new type of this theatre called IMAX 5D arose enhancing the 3D experience with two more sense stimulators – scent spreading system and mechanism dynamically moving with the visitor seat. Being, without any doubt, very interesting for all those actively involved, along with the surround sound it is not interesting in terms of human optical system fatigue.

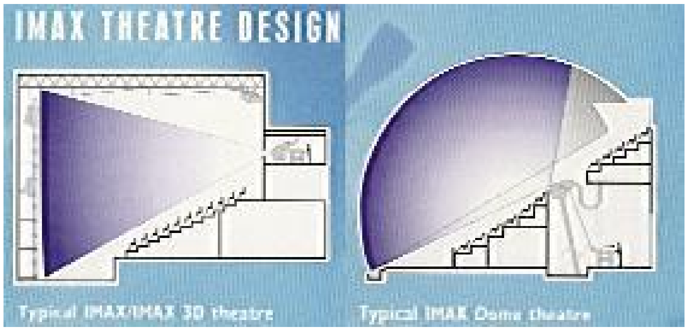


Fig. 5.1 IMAX 3D and IMAX Dome (taken from [49])

The IMAX cinema I carried out my surveys at was Oskar IMAX in Prague a representative of IMAX 3D technology. Flat rectangular projecting screen is 25 m wide, 20 m high and approximately 10 m distant. Capacity of the theatre is 149 people.

5.2.2 University stereoscopic apparatus

The AV MEDIA make apparatus owned by the university takes the advantage of the back-projection of light polarization (see 2.8.5) on high diffusional projection screen of size

2001 mm to 1501 mm, max. resolution of 1024x768 and implied pixel size of 2 mm. The maximum refresh frequency of the projectors is 75 Hz.

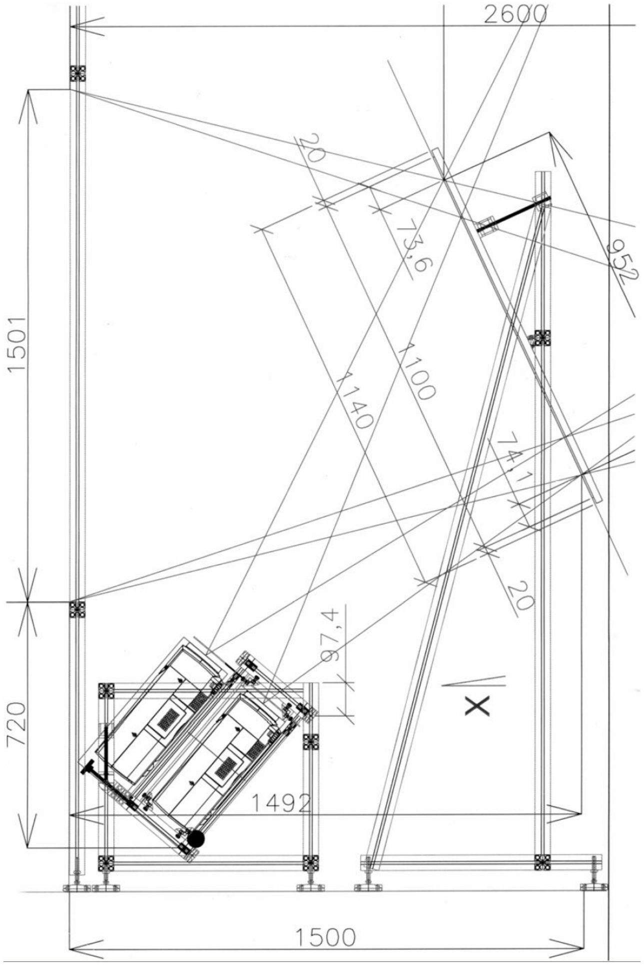


Fig. 5.2 AV MEDIA stereo-wall side view outline (taken from manual of the device)

5.2.3 CRT screen

For the experiments performed on the personal computer at my place I used 19” CRT display screen Iiyama Vision Master Pro 454 (see Fig. 5.3). This screen provided sufficient clarity and contrast to use with anaglyph glasses (see 2.8.2) and shutter glasses (see 2.8.3). The shutter glasses (eDimensional make) were used for experiments just marginally though. The display provided 1024x768 resolution with 150 Hz refresh frequency. Each eye was provided with 75 Hz image refresh frequency. For experiments with anaglyphs I used red/cyan classic paper anaglyph glasses.

5.2.4 Mobile LCD screen

At the moment almost everyone owns a mobile phone. These little devices provide more and more functions including picture taking or movie shooting, however in most cases with very limited quality. The mobile phone I carried out my experiments on was Sony Ericsson S700i (see Fig. 5.4) with 1.3 mega pixel digital camera with fixed focus which corresponds to 1280 x 960 pixels of sufficient quality for good light conditions. The video output was limited to 176 x 144 pixels with rather high compression. Big 57 mm (2,25 inches) display of 320 x 240 resolution and 260.000 colour shades managed reproducing graphical output adequately. As well as on the CRT screen there were used red/cyan anaglyph glasses.

Fig. 5.3 Iiyama Vision Master Pro 454

Fig. 5.4 Sony Ericsson S700i

5.2.5 Software apparatus

All the pictures or movies were created in the 3D Studio MAX 2.5 the educational license of which was owned by the university. Picture modification was done on Adobe Photoshop 5.0 and Microsoft Painting 5.1. Anaglyph pictures were produced by Anaglyph Maker 1.08. For movies modification created with parallel axes there was used AviSynth 2.5.6 application, able to work, among others, with two separate movies and providing lots of functions (wrap, crop, shift etc.). Stereoscopic movies created this way were run on freeware Stereoscopic player 0.9.4.

5.3 Experiments

5.3.1 IMAX cinema

IMAX cinema is one of the best places, where the one can see both positive and negative impacts of long-term observation on the users' visual system in practice. There are numbers of motion pictures, whether they were made by shooting real scene, made artificially by computer software using state of the art stereoscopic techniques or by a combination of both. Somewhat problematic and deteriorating the final visual outcome is the fact that the visitors are spread out over different places in front of the screen seeing the picture from different distances and angles. Different theatre dimensions are also common phenomenon the whole world over. However this could be against the effort of the movie makers as the picture parameters are fixed and different user position or cinema proportions directly affects the visual outcome. In an ideal case we would have a cinema with one visitor at a time, shooting picture accurately calculated according to the parameters of the current apparatus and viewing position. IMAX 3D seems to be more prone to this disadvantage than IMAX Dome though, as the concept of semi-spherical screen and specific projector position gives broader view adjustment possibility. An elevator in the projection room can raise the projector anywhere from 3 to 6 meters to ensure high-quality visual outcome. Anyway, the IMAX theatre guide advises visitors to concentrate on the centre of the projection screen, or close their eyes for a while in case of any visual inconvenience.

My aim in this experiment was to examine conditions and impact of professional 3D projection on lay public of different age and gender. Every movie my survey was carried out on I personally went to see and made rough measuring and judging of particular scenes. There was questioned sixty-seven people altogether on three movies. The survey was anonymous, conducted right after or even during the film running. Answering simple questions led to subjective evaluation of the film as whole or just specific parts possibly complementary information associated with their personal IMAX experience.

Particular queries dealt with: age of the viewer, education, number of already undergone performances of this kind, ocular defects and imperfections, ability to use stereograms, pleasant or unpleasant experience during and after the observation, overall feelings (1 – absolutely no discomfort, 2 – comfortable but not like in the reality, 3 – comfortable with some exceptions, 4 – sometimes very uncomfortable, 5 - mostly uncomfortable), sitting place in the theatre, sequences somehow interesting, comparison to the real world viewing and other remarks.

Three movies were subjects of my survey:

- *Space Station (SS)* – It is a cinematic journey to the International Space Station, where audiences can experience for themselves life in zero gravity aboard the new station, which becomes new home for cosmonauts from Florida's Kennedy Space Center and Russia's Baikonur Cosmodrome. There were used mostly interior scenes with occasional exterior shots.
- *Mysterious Deep (MD)* – On the bottom of the sea, there are places where human haven't ever got. A mission of enthusiastic scientists along with NASA experts aims to explore such inhospitable places of undersea thermal springs. There were used mostly exterior scenes with occasional interior shots.
- *Alien Adventure* (AA) **-** Moving through the galaxy a group of aliens head toward the planet Earth with a goal of establishing a new home for their people. By accident they touch down in the middle of a theme park. From now on the movie is a mix of third-person views of pretty wild roller-coaster drives.

First two motion pictures contained both real and synthetically generated scenes with substantial predominance of the real ones. The last picture was rendered exclusively by computer systems. Durations of these films were similarly about 45 minutes.

5.3.2 University stereoscopic apparatus

The university apparatus helped me to use light polarization technology for experiments aimed on particular cues of specifically set parameters values whether it was for static pictures, movies or real time rendered scene. Device itself was of a good quality. Just polarization direction for the left eye could have been adjusted more precisely to avoid noticeable oversized ghosting for some specific pictures. Also slight vertical disparity was present, which was a consequence of bad projector positioning. Both defects weren't any significant and had fractional impact on the experiment results.

All the tests were carried out on the university staff and students. Apart from the IMAX survey, where the absolute majority of those participated were laypersons, there were people well familiarized with the stereoscopics and its technologies. However, technology acquainted persons usually know how to exactly evaluate certain situations during these kinds of surveys they also suffer from prejudice and facts of common knowledge which could influence the outcomes.

There were number of experiments conducted during the studies of the problem. Notions of different participants were took down, analyzed and processed into identified outcomes. The aim was to generate visual output complying with more or less intentionally specified attributes. Having all attributes of the scene under control, including the minor ones, is both very hard and even unnecessary, as the subjective evaluation could be heavily influenced by an unnatural visual output (e.g. SIRD or classic stereograms complying sufficiently with binocular fusion conditions, although eliminating all but one (disparity) visual cues and thus providing rather deficient visual output (see 2.8.1)). Neither all possible combinations of applicable cues were feasible. That is why just a limited and conscientiously designed selection of scenes were picked out, filling the potential of stereo-graphics as much as possible.

- *Static balls* – two cameras shooting scene of six balls of the same size and different colour. Constituent balls were placed in different positions in the scene depth (see Fig. 5.5), resulting in pictures with varying disparity. From the closest to the farthest one there was a distance of 26 m (see Table 3). Each ball possessed a bump map in order to give a viewer more cues helping to fuse its separate images into one. The surface segmentation is an easy way how to increase visual frequency and make 3D objects plastic rather than being perceived as flat images placed in different parallax planes. The scene was rendered using infinite depth of field thus all objects in the viewing field were sharp.

		Ball 1	Ball 2	Ball 3	Ball 4	Ball 5	Ball 6
	Relative position d_2 [mm]	0	3500	8000	13000	19000	26000
Images (nearest ball distance d_1 [mm])	Pic. 0 (1270)	-2°37’57’’	0°23’57’’	1°56’01’’	1°07’55’’	1°14’27’’	1°18’27’’
	Pic. 1 (2000)	-1°07’30’’	0°32’43’’	0°58’30’’	1°09’00’’	1°15’00’’	1°18’45’’
	Pic. 2 (2900)	-0°18’37’’	0°40’47’’	1°01’06’’	1°10’11’’	1°15’37’’	1°19’06’’
	Pic. 3 (3650)	0°03’41’’	0°44’04’’	1°02’58’’	1°11’05’’	1°16’06’’	1°19’22’’
	Pic. 4 (4500)	0°20’00’’	0°50’37’’	1°04’48’’	1°12’00’’	1°16’36’’	1°19’43’’
	Pic. 5 (5150)	0°28’50’’	0°53’35’’	1°06’03’’	1°12’39’’	1°16’57’’	1°19’53’’
	Pic. 6 (6000)	0°37’30’’	0°56’50’’	1°07’30’’	1°13’25’’	1°17’24’’	1°20’09’’
	Pic. 7 (6650)	0°42’38’’	0°58’58’’	1°08’30’’	1°13’58’’	1°17’43’’	1°20’21’’
	Pic. 8 (7150)	0°45’56’’	1°00’25’’	1°09’12’’	1°14’22’’	1°17’57’’	1°20’30’’
	Pic. 9 (10000)	0°58’30’’	1°06’40’’	1°12’30’’	1°16’18’’	1°19’08’’	1°21’15’’
	Pic. 10 (15000)	1°08’60’’	1°21’29’’	1°16’18’’	1°18’45’’	1°20’44’’	1°22’19’’

Table 3. Positioning of the balls in the scene and their parallaxes (used equation(6) in 2.5.2)

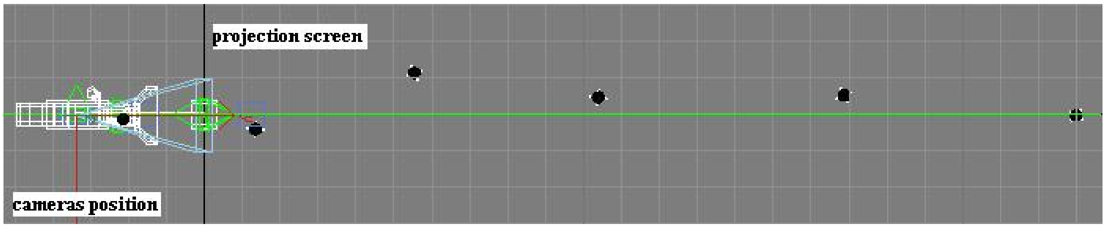


Fig. 5.5 Positioning of cameras and objects (balls 1 to 6 - counted from left to right) in the rendered scene. Distance d_1 ranges between the first ball (most left side on the picture) and centre of camera lens – increases with picture number (0 to 10). Distance d_2 ranges between every single ball and reference position point given by ball 1 centre.

- *Text reading* – one page containing plain text in black and white was displayed to the subjects for 5 minutes to investigate effects and impacts of mid-term observation of high-value disparities. The picture was prepared with absolute negative parallax of 60 pixels for viewing from distance of 2 meters. This parallax created disparity of –3°26’3’’ of arc making the two pictures hard but not impossible to combine. Resulting picture was designed for the subjects to appear about 700 mm distant.
- *Comparison of two movies* – two movies of the same informational content but different parameters were designed in a way the one represents manner in which the stereoscopic products should not be created and the other one is its exact opposite in the meaning of correct 3D video parameters settings. Specific stereo defects were applied particularly to some of four parts of the picture, the relation of which was described in the brackets (1 - 4) after each point in the list below. (1) Six balls moving along concentric ellipsoid paths in five layers (see Fig. 5.6). (2) Six balls moving in the opposite direction in two layers placed in front of the screen in a way to cross the screen edges. (3) Six torus knots in complementary colours going round the circles the centre of which was abruptly changing its position in the scene depth simulating cutting in a movie (see Fig. 5.7). (4) Several different geometrical objects going along their paths not interacting with each other plus incorporating an effect of snowing.

The scenes were created according to the main causes of visual strain summarized in chapter 4.1. Specifically it was:

- Breakdown of the accommodation & convergence relationship (1-4) - automatically follows from the concept of the apparatus with fixed projection screen. Its negative impact raises with higher parallax values.

- High values of the parallax (1,4) – (1) The main axis of the ellipsoid paths had a viewer aspect so that each layer, the balls were gradually moving along, provided higher values of parallax (see Table 4). (4) Number of miscellaneous objects moved within the scene depth from -2200mm (-2°32’14’’) to +4000mm (-0°48’00’’)

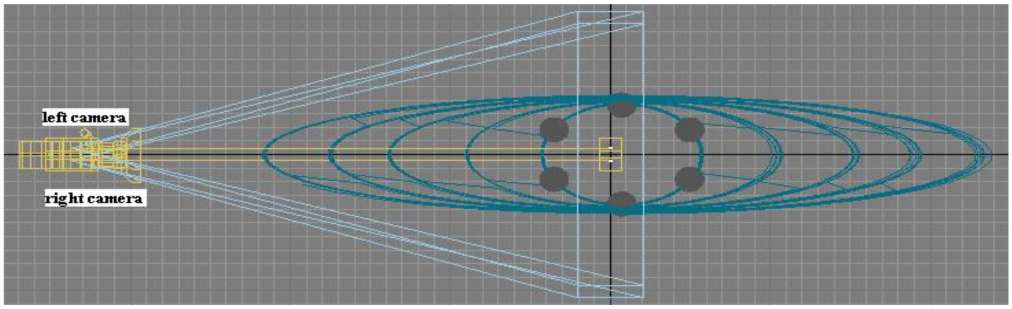


Fig. 5.6 Ellipsoid trajectories of moving balls in the first part of the movie (counted from centre)

	Farthest point [mm]	Disparity	Nearest Point [mm]	Disparity
Ellipse 1	-400	-0°11’37’’	+600	0°13’10’’
Ellipse 2	-900	-0°31’09’’	+1100	0°21’31’’
Ellipse 3	-1400	-0°59’59’’	+1600	0°28’14’’
Ellipse 4	-1800	-1°35’16’’	+2000	0°32’43’’
Ellipse 5	-2200	-2°32’14’’	+2400	0°36’36’’

Table 4. Ellipsoid layers (negative values symbolize object position in front of the reference screen)

- Crosstalk (1,2,3,4) - there were used highly contrasting colours to the black background, which were producing noticeable crosstalk throughout the whole picture (mainly green, white, red and yellow)
- Conflict between interposition and parallax cue (2,4) – (2) Depth of moving balls ranged from -1500mm (-1°07’29’’) to -850mm (-0°28’52’’). (4) Moving hose object, among others, intersected the left screen edge at -2100mm (-2°14’57’’).
- Technical imperfection and setting of the 3D apparatus (1-4) - Apart of the trifle imperfections of the apparatus already mentioned there was used low refresh frequency of 60 Hz.
- Expanded (infinite) depth of field (1,4) – Significance of this phenomenon raises with disparity differences of the objects. Thus it cannot be directly suppressed as the movie producer cannot fully instruct the viewer to focus on a particular scene spot.

- Sudden changes in the depth of the scene (3) – Centre position ranged from -800mm (-0°26’40’’) to +5300mm (0°54’12’’) which concluded in disparity difference of 1°20’52’’. (depicted in Fig. 5.7)
- Excessive motion content (1,2,3,4) - great values of speed and motion were applied to the whole picture.
- Geometrical distortions between left and right images (4) – as a part of the experiment there was an attempt to provide users with slightly different visual information for each eye. Snowing for the right eye in part (4) was left out in particular.

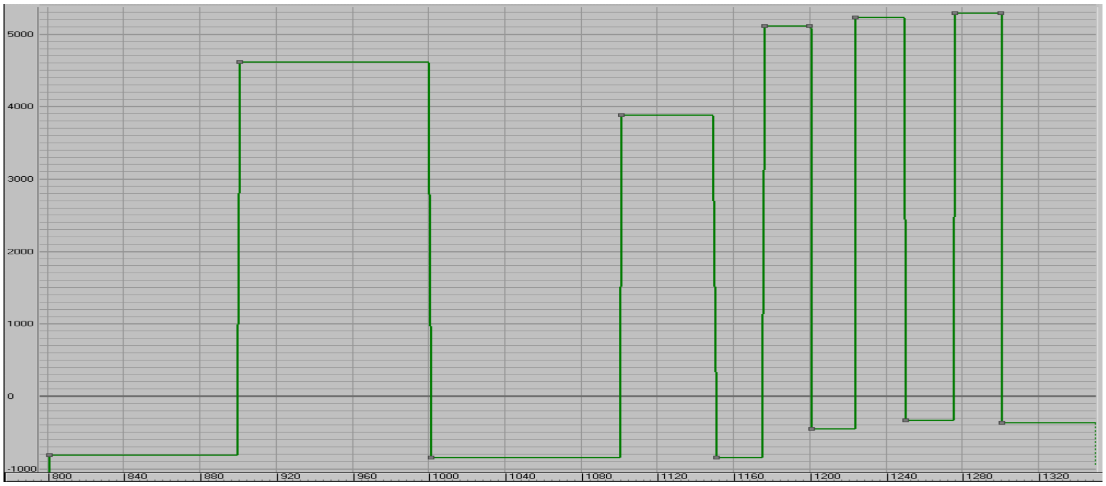


Fig. 5.7 Position changes in depth and time (taken from 3D MAX application)Horizontal axis represents number of frame (=time), vertical axis represents distance from zero parallax plane in millimetres.

When making the second movie representing the correct stereoscopic parameters setting there had to be paid attention to all of the points described above and either eliminate or set them to admissible values resulting in pleasant 3D perception. First the overall speed was reduced by prolonging the movie parts in order to get half-speed content and twofold duration. (1) Moving balls got bump mapping and blue and red colours, which made them more plastic and not causing so much crosstalk. The disparity of the balls was reduced to the range of -400mm (-0°11’37’’) to +500mm (0°11’15’’). (2) The two layers were shifted into the depth range of 0mm (0°00’00’’) to +600mm (0°13’10’’) possessing the bump mapping and colouring from the previous part. (3) The abrupt changes of depth and position on the screen were reduced sparing viewers the excessive eye movement and disparity difference. Some of the cuts were replaced by smooth movement from one utmost point to another. The range of depth of this part was from -300 (-0°08’27’’) to +800

(0°16’44’’). (4) Colour of the snowing was darkened. The paths of all objects were reduced to resulting range of -800mm (-0°26’40’’) to +1700mm (0°29’25’’). Interposition of an object with lateral screen edge was reduced to maximum -400mm (-0°11’37’’). It needs to be emphasised that the overall visual information was preserved not depriving the viewer of anything of the movie content.

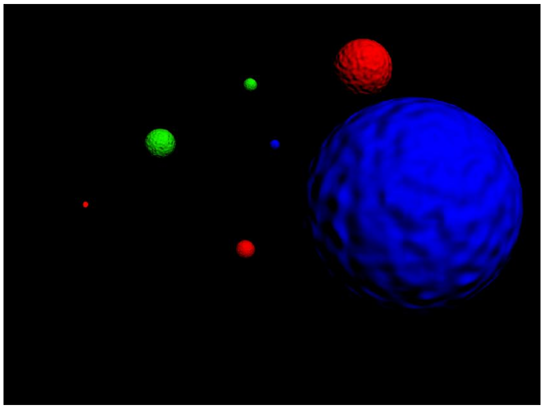


Fig. 5.8 Static balls

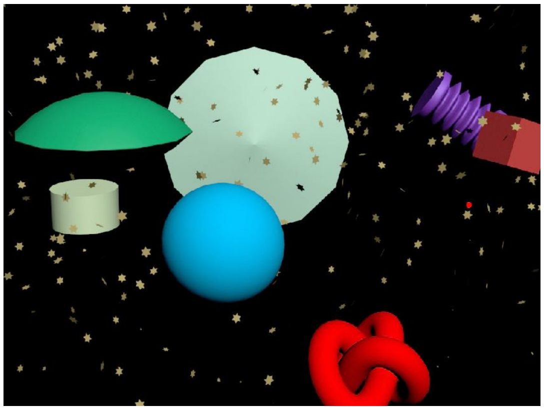
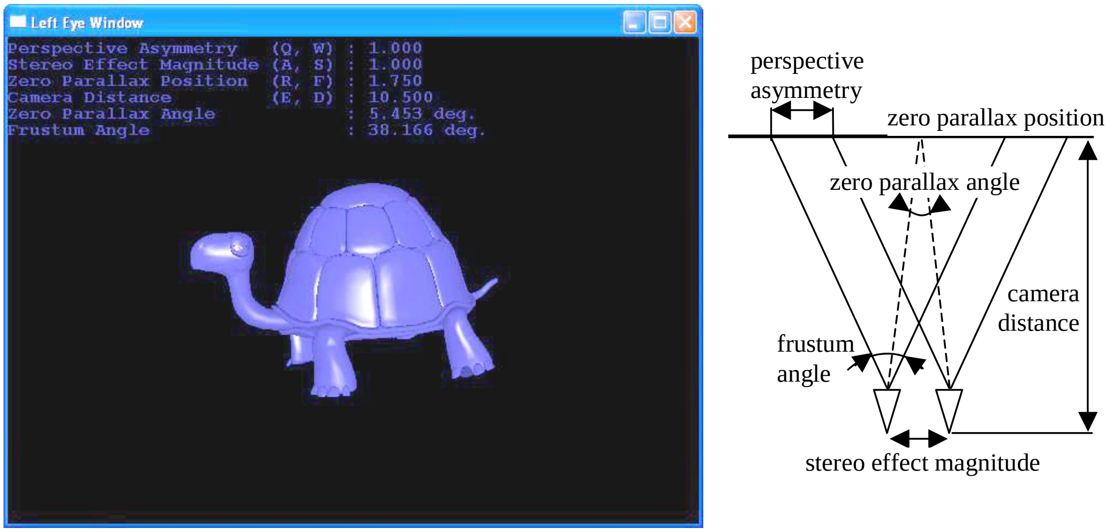


Fig. 5.9 Comparison of two movies

- *Stereoscopic application* – the C++ application (developed by Zbyněk Novotný) allows user to observe real-time rendered objects and adjust parameters to gain desired stereoscopic output. There is a possibility of either loading any object in .tri geometrical format or using default textured cube although only one object at a time. Objects are rotating according to the algorithm or can be paused in the current position. All the scene settings are pictured in the upper left corner (see Fig. 5.10). The parameters are mostly represented by relative value as they would have to be recalculated to the values corresponding to the displaying apparatus. For our calculations there was needed to know that one unit of ‘perspective asymmetry’ corresponds to 130 mm of absolute parallax.

As a part of our research we tried with a help of this application to find image fusion limits. The viewer was provided with an object the absolute parallax value of which was smoothly increased until the viewer wasn’t able to keep the images fused in one. After that the parallax value was smoothly decreasing until the participant was able to fuse them again.

The cameras in 3D Studio MAX application were placed 91,64 mm apart with parallel axes. Distance of imaginary projecting screen was set to 3500mm, which along with the cameras interposition distance made up recommended viewing angle of 1,5°. The distance was chosen according to the recommended value of optimal visual frequency of 16 cycles per degree and three-times the height of the screen (see 3.2.2), even though it led to absolute parallax gain of 91,64mm for infinite objects and thus possible positive diverged parallax occurrence. This kind of parallax appears in our case when the object exceeds distance of 12m from the viewer. The aim was to examine this phenomenon as well. This fact needed to be taken into account for the '*Static balls*' experiment only. Fields of view of the cameras were set to 32° of arc corresponding to their distance and projection screen size.



```
Perspective Asymmetry   (Q, W) : 1.000
Stereo Effect Magnitude (A, S) : 1.000
Zero Parallax Position  (R, F) : 1.750
Camera Distance         (E, D) : 10.500
Zero Parallax Angle            : 5.453 deg.
Frustum Angle                  : 38.166 deg.
```

Fig. 5.10 Stereoscopic application

5.3.3 CRT screen

CRT screen in our case represented just an informal way of dealing with stereo pictures produced mainly by a digital camera or graphic application. There was number of experiments conducted to simulate either known facts or our assumptions. Some of them were carried out both on CRT screen and even university apparatus. All the results were included in this part though because of their value as an explanatory example but minor experimental significance.

- *Digital camera photos* – several interior and exterior photos were taken without any exact method of calibrating. The output itself suffered from a problem of pictures taken for either eye not simultaneously. Especially when working outside it had to be guaranteed that the picture will contain 'adequately equal' scenes (objects, brightness etc.). In order to get proper stereo-effect the interlens distance was adjusted depending on nearest object distance. If we want to maintain recommended viewing angle of 1,5° in case of the street image (see Fig. 5.12) where the closest object is a tree 5 meters far from the camera it follows that the interlens distance should be about 130mm. Although in reality the distance was set to 240mm when making pictures of snowing in the street (see Fig. 5.12).

- *Keystoning error* – this phenomenon appears when converged camera axes are used for shooting the scene (see 3.1.1). Vertical disparity is directly proportional to the angle formed by cameras. For the purpose of presentation there was created an animation (see Fig. 5.11) where cameras axes convergence ranges smoothly from 0° to 10°.
- *Film effects* – as the stereoscopic technologies are part of movies production industry the film effects might be used as in case of normal movies. ‘Crossing’ and ‘wiping off’ of two scenes and ‘fading out’ effects were used.

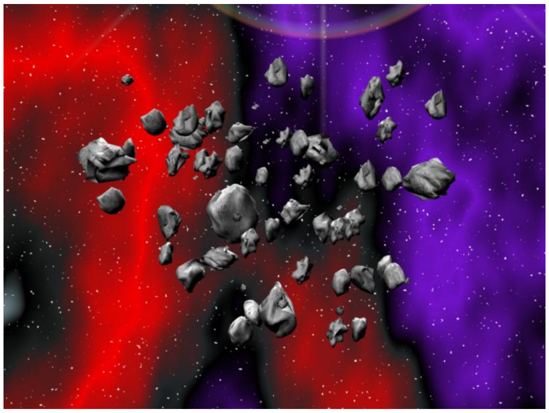


Fig. 5.11 Asteroids cloud

Fig. 5.12 Street – digital photo

- *Shifted frames* – unsynchronized animation frames are evidently source of irrecoverable 3D perception breakdown as the direct consequence is incontrollable disparity disorder. Depending on direction of the object movement it could also lead to interesting visual outcomes. A scene with rotating spheres has been designed. The time difference between corresponding left and right frames ranged from 2 to 10 frames while frequency was 30 frames per second.
- *Movie with non-infinite DOF* – the problem for current technologies is the necessity of having the whole scene in focus. The aim of ours was to create a scene suppressing negative impacts of high values of disparity by blurring the objects depending on distance from the imaginary projection screen (zero disparity plane). The only possibility how to employ this method is to compel the viewer to concentrate on a concrete spot in the screen (usually middle of the screen) through making use of something interesting not tempting

the one to change the gaze direction. This is what we tried to simulate in this experiment. Six balls of green colour going along elliptical path in the range of -2400mm (-3°16’14’’) to +2400mm (0°36’36’’), which results in a massive non-recoverable double vision. As an object of interest we used rotating hedra object of red colour changing it parameters throughout the movie and thus creating a spectacular attraction. Setting the cameras parameters *Focal Range* = 1000 and *Focal Limit* = 2000 which at the utmost points resulted in blurring of about 50% of the object radius.

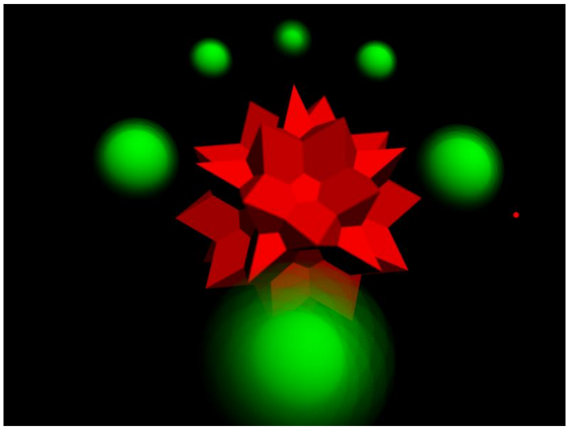


Fig. 5.13 Movie with non-infinite DOF

5.3.4 Mobile LCD screen

These experiments were placed into this work as a matter of interest showing the growing possibilities of such devices. Sufficient resolution and colour depth allowed us to watch static pictures. One exception represented .gif format offering moving pictures through sequential arranging of pictures into one set. Rotating torus knot and ‘bubble matrix’ scene were objects of the investigation. Miniature size facilitated operating and swift changing of absolute distance of the screen.

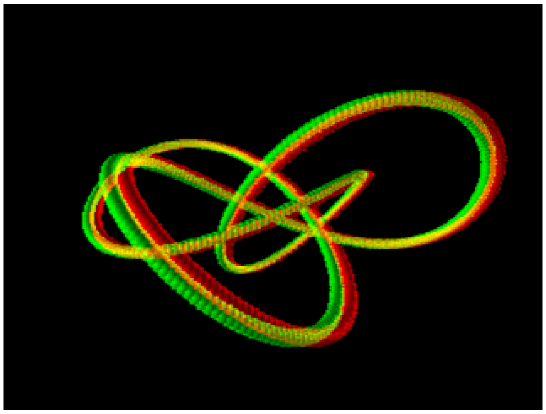


Fig. 5.14 Rotating torus knot

Fig. 5.15 Bubble matrix scene

5.4 Experiments results

5.4.1 IMAX cinema

Particular scenes of the films were generally well perceived creating solid three-dimensional perception. However, there were sequences, meant by designers to produce impression of very near objects, of extremely high parallaxes resulting in non-recoverable double-vision. These objects produced disparities of about 7° which corresponds to the sitting place positioned in the middle and represented object of 0,5m distant from the visitor. These values are not easily perceptible especially when displayed for such a short period of time. Visitors in the rear rows profited from the extra distance and on the contrary those sitting in the very front suffered the most. The difference could be up to 4°30’ in the rear (15m distant) and 12° in the front (6m distant). Whereas the viewer in the front would have the object 30cm distant the viewer in the rear wouldn’t be even able to reach it at the distance of 75cm (see 3.1.3 and 3.2.2). However the front one could not fuse these two separate images into one, the rear one could fuse these images with some effort and see the resulting 3D image.

The overall audience viewing comfort was evaluated in scale ranging from 1 (comfortable) to 5 (uncomfortable). Results classified according to these values are summarized in Fig. 5.17. 3D sensation was judged uncomfortable either sometimes or mostly for about 17% of the viewers. The average value equals to 2,39 points which means that the perception was mostly ’comfortable but not like in the reality’ or ‘comfortable with some exceptions’. Taking in consideration the viewers’ position we get interesting result underlining the assumptions from the previous paragraph (summarized in Table 5). The closer to the screen, the higher level of discomfort during the observation. Table 6 represents a comfort evaluation related to number of visits of the IMAX theatre which leads to two possible conclusions: 1) Visitors who have gone through more visits are less likely to be experiencing visual discomfort thanks to the practice; 2) Visitors who have experienced unpleasant feelings during the show are less likely to come again. The second choice seems to be more probable in this case although any former stereoscopy experience is undoubtedly taken as an advantage. Taking the stereograms viewing skill as a minor auxiliary stereopsis experience we get these mean figures related to three possible answers to question ‘Can you use and see stereograms?’: can – 2,2; cannot – 2,8; don’t know – 2,3.

Position	Average evaluation
Front	2,9
Middle	2,3
Rear	1,9

Table 5. Average values classified according to the sitting position

Num. of visits	Num. of participants	Average evaluation
1	23	3,0
2	26	2,1
3	10	2,3
>3	8	1,9

Table 6. Comfort evaluation related to number of visits of the IMAX theatre

On average, older people are supposed to be more prone to unpleasant feelings experiencing during the observation. This outcome is a consequence of overall viewing comfort of the participants related to their age (see Fig. 5.16). The linear approximation is just emphasizing the apparent inclination rather than showing expected average evaluation related to age. That is because of lag of the ‘older generation’ representatives. While arithmetic mean of the age reached 25,2 years (median 24 years) ranging from 7 to 57, full 67% (45) of subjects were not younger than 15 and not older than 30. Comfort values related to the age class are depicted in Fig. 5.18 showing clear generation differences.

Within the inquiry there were posed a questions about pleasant or unpleasant experience during and after the observation. The most common complaints were ‘visual discomfort’, ‘having a headache’ and ‘feeling a sickness’ (summarized in Table 7).

Have an eye lacrimation	8	Have a headache	21
Pressure in the forehead	5	Overall tiredness or lassitude	4
Feel a sickness	17	Visual discomfort	35
Have a shadowiness	2	Feel dryness in the eyes	3
Feel an eye-strain	13	Unable to focus stably	8
Unable to concentrate attention	6	Feel a blurring	4
Feel a pain in the eyelids	1	Have a dizziness	3
The whirr in the ears	2	Feel a pain in the eyes	3
Weird unnatural feeling	12	Have a tic in the eye	2

Table 7. Visual fatigue symptoms after or during the observation + concrete numbers of those affected out of 67

As for the particular pictures, there were some differences in collected pieces of information from the subjects. Generally all computer made scenes (whole AA, and partially SS and MD) were perceived comfortably resulting in very impressive three-dimensional sensation. Having mentioned already, real scenes taken by cameras (AA and MD) were, with some exceptions, well perceived also with mostly unnoticeable parallax cuts and smooth movement through the scenes. The AA movie was representing a departure from the rule in terms of tranquil speed and movement. Scenes full of crazy roller coaster joyrides compelled many to close their eyes for a while following the advice of IMAX theatre guide and also caused most of unpleasant feelings or even health

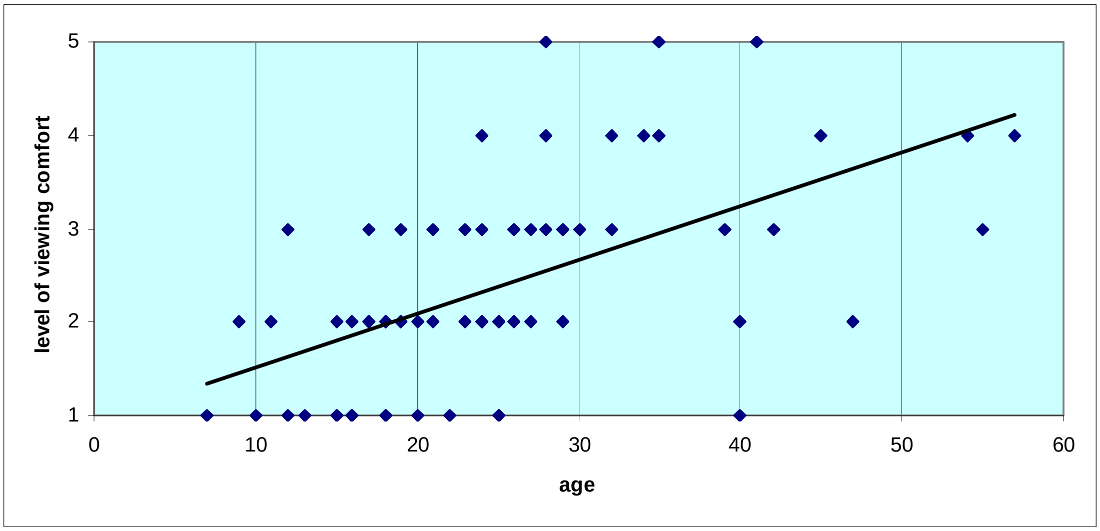


Fig. 5.16 Dependency of audience viewing comfort on their age

problems (86 out of 149 from Table 7). The most favourite scene to the majority was a computer made usher hanging it the space against the one-coloured background.

No other dependencies were found whether education or ocular defects and imperfections were taken into account. All these outcomes need to be risen above a little since much higher number of participants would be needed to get precise figures reflecting the reality more closely. However, quite clear outline has been drawn thanks to this work.

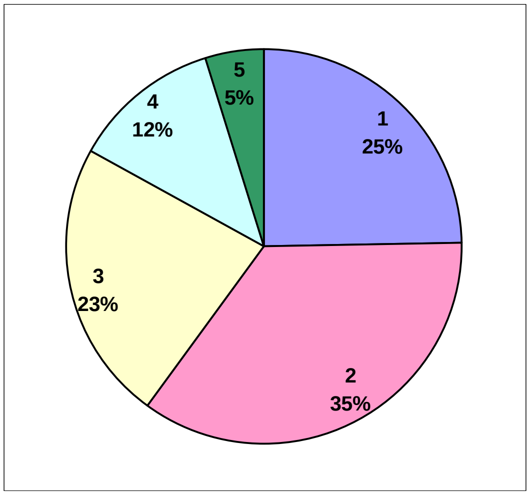


Fig. 5.17 Overall audience viewing comfort

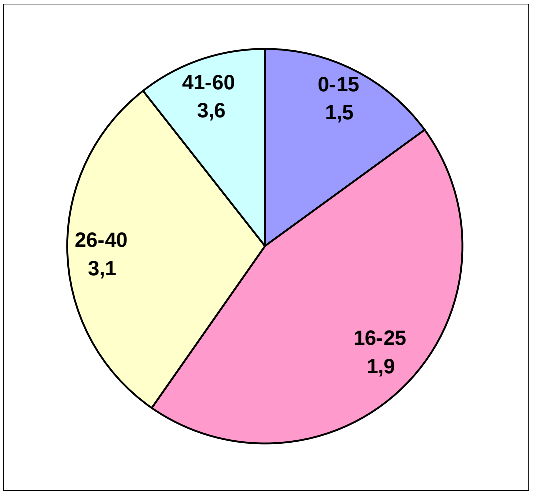


Fig. 5.18 Average comfort values related to age class

5.4.2 University stereoscopic apparatus

During the tests all subjects were asked for close cooperation and commenting on anything related to the current observation that comes to their mind.

- *Static balls* - this experiment should have proved the ability of subjects to determine mutual (relative) positioning of the objects, colour and infinite depth of field usage impact. All subjects were watching the scene from 3,5 and 2 meters distance. The 3,5m observation distance produced better spatial perception according to the participants' comments. They also appreciated scenes with slight or none negative parallax near to zero parallax plane (images 2 – 6, balls 0 - 2). Even though there was a bump mapping used to enhance spatial perception, thanks to low object complexity many subjects evaluated them as being flat.

Hardly any participant determined the relative position of the particular balls incorrectly. Some deficiencies occurred for the objects in the high positive parallax. This finding can be ascribed to diverged parallax emerging for the balls distant more than 12m. The parallax cue seems to be absolutely sufficient when trying to evaluate an object depth order. It applies to the distance estimation in case of using a referential object in the real world also.

The colours substantially influenced the overall visual sensation. The green colour predominated at crosstalk (ghosting) creation since it was the brightest one and polarizing filters of the glasses were not able to separate particular images completely. The subjects claimed seeing three objects instead of one. Such problem did not occur in case of blue and red colour. In order to get rid of the ghosting effect the viewers screwed up their eyes. The scene depth was enhanced this way to the exclusion of objects detail loss.

- *Text reading* – all the subjects achieved fusion of shifted pictures after a while of concentration and started reading the text. Most of them found problematic to skip to the next line since the very fast eye movement prevents the eye muscles from keeping convergence on such high parallax value all the way across the sheet. Not even moving of the head was recommended because it mostly led to disorientation. Once the convergence had been lost it took some more effort to get the fusion again. With each minute it was harder for the observers to maintain a single vision. The muscles got tired and the vision started to be deteriorated. It was also found that interposition with the frame is very disturbing which thanks to the edges near to the beginning and ending of text lines was rather frequent problem. The interesting fact is that the observers were not able to distinguish negative and positive parallax of such high values from each other in the very endeavour of fusing them. The negative impact of the diverged parallax was felt quite more significantly though. 3 out of 15 subjects experienced an eye-strain during the trial.
- *Comparison of two movies* – According to our assumptions ‘good’ movie made an impression of being much suitable and easier to watch mostly with a nice three-dimensional sensation. There were picked out several problems which were encountered in both pictures: 1) Black background does not help determining the absolute depth of the objects. It is always convenient to have something to relate the object depth to (like in reality). 2) Insufficient smoothness of the video led to spatial perception destruction. That is why all the videos were converted from 1024x768 px. to 640x480 px. resolution as the higher resolution was not running smoothly on the stereo apparatus’ PC. 3) In the situations where a red ball is passing behind a blue one there was sometimes a cue collision noticeable at the viewer. Parallax cue positioned the blue object before the red one whereas the blue colour induced a feeling of positioning behind the red one. This

problem has risen after the animation was paused. 4) Some of those participated complained about a physical laws drawback residing in mutual object intersection which was said to be a source of viewers' confusion. 5) It has also been found that even though the film cuts are very fatiguing those back-to-front are worse than the front-to-back ones.

Subjects' evaluations for particular movies were summarized in the pros & cons list:

'Bad' movie	**'Good' movie**
PROS	**CONS**
- good looking rotating torus knots - acceptable cuts from rear to front	- sometimes to plain -> no 3D effect - depth order guessing for blue and red balls
CONS	**PROS**
- abrupt convergence change after cut - very fast - missing motion blur - unable to focus on the snowing effect, very chaotic - insufficient smoothness of the playing - too high values of parallax - frame / scene intersecting - noticeable ghosting - perspective twisting - cuts are not apprehended as jumps within the depth of scene - user compelled to move his eyes too much	- bump mapping - film cuts are more suitable - slower and smoother movement - low parallaxes – very good looking scene with snowing - acceptable ghosting level

- *Stereoscopic application* – the application worked perfectly a helped us to set parameters influencing the visual stereoscopic output. Surprisingly for us, adjusting the absolute parallax values ('perspective asymmetry'), which merely horizontally shifted the rendered pictures, did not result in sense of smooth object moving towards/from the user. This phenomenon needs to be supported by more than just the parallax cue. Moving the zero parallax plane is accompanied by the moving of camera itself and thus apart from the object parallax change, the stereopsis strength and size of the object as well. Resulting effect is very real. It has been found also that for enhancing the stereoscopic effect it is contributing to use complex concave or hollow objects (e.g. wire sphere).

Participants who took part in the fusion limit experiment confirmed our assumptions that parallax values reached by smooth and gradual increasing is higher than the parallax limit values fused instantly. The participants also demonstrated that there is a possibility to increase fusion limit values through practicing. One trial followed by another helped the users to raise their previous result quite significantly. However, this eye exercising is very exhausting for those practising. The results are summarized in Table 8.

	Gradual change		Instant change	
Person	1. attempt	2. attempt	1. attempt	2. attempt
1	-9°05’51’’	-11°29’07’’	-5°34’34’’	-7°36’48’’
2	-10°00’48’’	-11°40’08’’	-6°19’03’’	-7°59’00’’
3	-8°32’15’’	-11°07’03’’	-6°59’04’’	-7°25’43’’
4	-9°01’03’’	-10°22’54’’	-6°36’50’’	-7°03’30’’
5	-8°10’05’’	-12°13’10’’	-6°07’56’’	-8°32’15’’
6	-8°32’15’’	-11°18’05’’	-7°14’36’’	-7°03’30’’
7	-9°38’41’’	-10°44’59’’	-6°52’24’’	-7°32’22’’
8	-9°05’51’’	-11°02’38’’	-6°41’17’’	-7°47’54’’
9	-7°59’00’’	-10°11’51’’	-6°25’44’’	-6°41’17’’
average	-8°53’54’’	-11°07’46’’	-6°32’23’’	-7°31’22’’

Table 8. Values o disparities after gradual or instant parallax provision with values of 1. and 2. attempt (used equation (6) in 2.5.2)

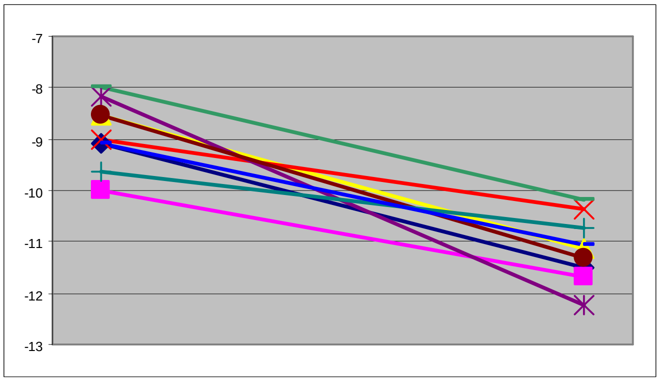


Fig. 5.19 Gradual parallax provision with values of 1. and 2. attempt

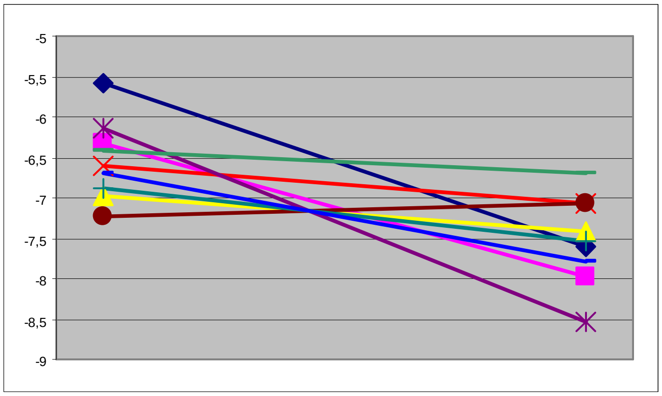


Fig. 5.20 Instant parallax provision with values of 1. and 2. attempt

5.4.3 CRT screen

- *Digital camera photos* – through this experiment we wanted to find out if there is a possibility of taking stereoscopic photos with one camera and without any special accessory (tripod, protractor etc.). The main concerns were to produce insignificant vertical disparity (had to be less than 3 min of arc) and thus the camera needed to be leaned against some straight horizontal board and the camera axes convergence had to be more or less parallel. The interlens distance needed to be estimated according to the nearest point in the scene. The outcomes were quite convincing. Even under these conditions the spatial effect has been reached. Although without two synchronized cameras taking photos at the same time we are restricted to taking pictures of static scenes only. The example of scene containing a movement represents a picture of snowing in the street. Even though the visual content is substantially different this picture doesn't feel that visually unacceptable and doesn't have any impact on the visual strain. Moreover the snowing represented this way could be for someone a reasonable substitute of the missing movement.
- *Keystoning error* – The source of this problem is hiding in different shape of camera optical reader (flat) and retina (curved). It was found that the vertical disparity as a consequence of keystoning error is directly proportional to the angle of their axes. The reason is quite clear. Having a box the front square quoins of the front plane are equally distant from the lens centre. Turning the left camera through an angle clock-wise right edge becomes more distant then the left one. Thanks to the perspective the distant one appears smaller and thus makes the vertical difference to the mirror image from the right camera.

There are cases when the converged cameras can be used though. The case is when the cameras are meant to shoot near objects without the possibility of decreasing the interlens distance. In this case the depth of the scene must be very low because with the increasing depth there emerge both keystoning error and high values of positive parallax. It can be seen in the animation with asteroid cloud which represents an attempt to create a scene which would evoke a sensation of fast object moving against the viewer. The scene depth parameter is too high and the result is a diverged parallax of the objects in the rear and the background. Such disparities make the picture imperceptible conveniently. In an extreme situation the left and right images can contain absolutely different contents.

- *Film effects* – one of the reasons for the current 2D TV to survive could be the current possibility of employing special film effects which do not occur in the real seeing. It has been found out that transitions from one scene to another used instead of common cut is in most forms useless. Only ‘fading out’ effect is absolutely natural and is applicable with no restrictions.
- *Shifted frames* – unsynchronized animation frames can be a serious source of spatial immersion degradation. It has already been mentioned in the ‘comparison of two movies’ where the exceeding data flow caused unsmooth running of the animations. We tried to simulate situation where the frame time shifting could be somehow useful. This shifting resulted in case of rotating spheres in enhanced horizontal and vertical disparity. Luckily up to the top shifting of 10 frames the vertical disparity was not noticeable. The horizontal disparity led to increasing of the scene depth. The balls in the consequence were running along the ellipsoid. On the other hand the same shifting applied to the left view would result in 2D/3D cues collision if the front spheres got positive parallax and the rear ones got negative parallax.
- *Movie with non-infinite DOF* – this experiment lived up our expectations. When the viewer stayed focused on the moving and morphing object the balls moving around were not any notably deteriorating the overall spatial percept as in case of infinite DOF. The objects around the ‘object of interest’ were blurred sufficiently. This technique is hardly applicable in practice because of two main reasons: 1) to avoid the user looking at the blurred object, it would be necessary to track user’s eye movement and recognize the object of interest 2) the movie would have to be real-time rendered just for one person.

Shutter glasses were used partly also. This technology suffers from two main sources of visual strain: flickering of the images and ghosting (= crosstalk). Flickering at this case did not arise because the frequency of 75 Hz was sufficient and the scene seemed adequately stable. Although during the testing there was considerable ghosting emergence making the scene almost imperceptible. This phenomenon directly depends on synchronization of the image screening alternation and opacity quality of the electronic shutters.

5.4.4 Mobile LCD screen

This device offered us enough comfort for full-bodied usage as a stereoscopic apparatus. Its smallness provided us with the possibility of easy manipulation and we could have observed the pictures in range of very near and very far distances. Thanks to small size of the display there could not occur a diverged parallax. The spatial effect was notably increasing with the distance. The best results were gained in case of usage in the absolute dark when only the reproduced 3D object was visible. The filtering of LCD display colours was indistinguishable from the filtering of CRT monitor. Obviously the orientation of the device determines the parallax type. Although when chosen incorrectly the other cues help us tell apart the problem and turn the device upside down (rotating torus knot gif file). The interesting finding was derived from accidental viewers' reactions. The whole half of them considered wrongly one orientation to be the correct one. Some of them were not able to choose the right orientation even after a warning, that 'something could be wrong'. There were even some of them who knowingly preferred the wrong orientation to the right one.

6 Outcomes

In this paper, a relationship between stereoscopic techniques and viewing comfort has been investigated. There has been a lot of theoretical and practical research conducted within this work. From the experiments described above there were concluded outcomes more or less confirming results of different research groups, which were dealing with the same problem before, supplemented with some new interesting ones.

Our eyes and brain work as very sensitive machine and basically any natural visual perception violation more or less affects the comfort related to it. Technical apparatus utilization might be accompanied by number of such phenomenons which are not possible to encounter in reality. Every subject exposed to such an artificial 3D percept may manifest absolutely different physiological reaction. Our eyes are a synonym of imperfect optical system. However, its innate ability is to conform to simulated conditions in such a way that even the weirdest stimuli can create satisfactory spatial sensation.

Majority of devices capable of reproducing stereoscopic images make use of fixed projecting plane. There is a substantial drawback related to such principle which was proved to be the most contributing to consequent unpleasant feelings. This drawback is ‘breakdown of the accommodation & convergence relationship’ which is unfortunately its non-removable property as well as ‘high values of the parallax’ problem following from it. Moreover, watching scenes with extreme parallaxes prevents the user from recognizing the pictures content at the expense of effort to keep them fused. It has been proved that limiting the depth within a range around zero parallax plane yielded less eye strain. For a three-dimensional sensation creation is not unconditionally necessary to provide high values of disparities. On the contrary, by reasonably making use of 2D cues along with microstereopsis it is possible to evoke adequate experience accompanied by less stressing conditions.

There is also a substantial drawback inseparably linked with these commonly used devices of stereoscopic scene parameters changing with size of the projection screen and angle and distance of watching. A combination of one person in fixed viewing position and one size of the screen which the picture was created for are applicable only to the kind devices like head-up display but not to IMAX or 3D HDTV. Technical diversity and necessity to provide a picture to a group of people makes precise reproduction impossible. The only solution known so far would be utilization of another kind of technical equipment. An exception among 3D visual apparatuses constitute those with movable projection screen, which partly solves the issue or those based on holographic projection, which are the most ingenious devices, having perfect features of real scenes. However, thanks to very high acquisition costs they are employed mainly just for experimental and research purposes (for more see [27],[50]).

All the results and pieces of knowledge derived from our experiments were described closely in previous parts of this paper. A further most important or those worth highlighting are:

- In addition to precise device parameters adjusting the crosstalk can be suppressed by reasonable using of colours in favour of less contrasting ones.
- Conflict between interposition and parallax cue is making a viewer confused rather then visually tired.
- Expanded (infinite) depth of field cannot be fully repressed for current technologies but some particular scenes may to a certain extent take an advantage of pointing out (focusing on) an object of interest by narrowing the DOF parameter accordingly.
- Converged camera axes can be used mainly just for shooting a distant single object. Otherwise vertical disparities may emerge. Probably this problem could be completely rid of by using of cameras with a scanning component in a shape of eye retina.
- Sudden changes in the depth are better tolerated when the movement is front-to-back rather than the other way round. Gradual changes should be preferred to the step ones.
- Excessive motion content is a common problem of both 2D and 3D movies. A subject should not be compelled to change direction of viewing greatly nor quickly.
- Image and screen are supposed to be set to a sufficient level of brightness.
- The longer the subject is exposed to unnatural visual conditions the more is likely for any health side effects to occur and the longer it takes to our optical system to restore to its original state in terms of physical reactions on reality.

- Health and age of a viewer may contribute to visual fatigue. Some individuals may not be able to perceive stereoscopic scenes easily at all. Better results can be achieved by a practice though.
- For enhancing the stereoscopic effect it is contributing to use complex concave or hollow objects.

At the moment, the stereoscopy is mainly a part of entertainment industry. But there are fields like medicine or research where these new technologies come in useful much more than now after they reach sufficient technological development and favourable acquisition costs. Although, it is hard to believe that stereoscopy would replace the current visual representation technologies totally. There will always be a lot of reasons why there should not be used visualization containing depth content.

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Appendix A – Selection of coloured pictures

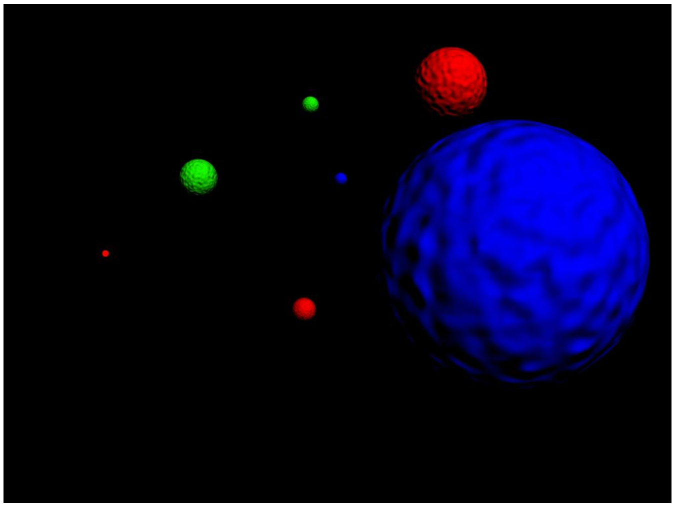

Fig. 5.8 Static balls

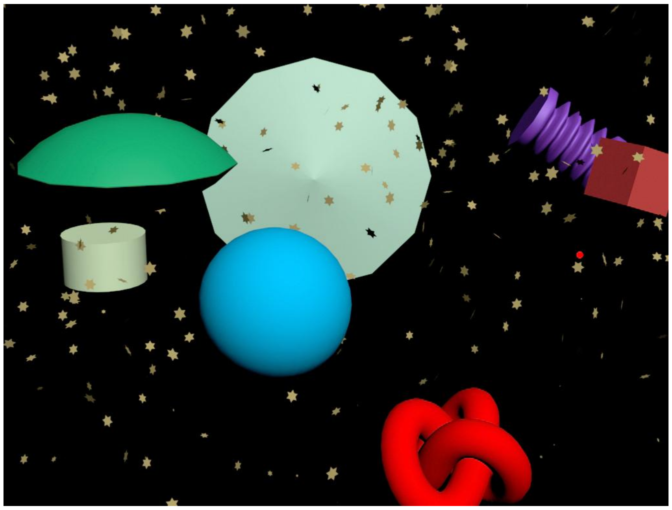

Fig. 5.9 Comparison of two movies

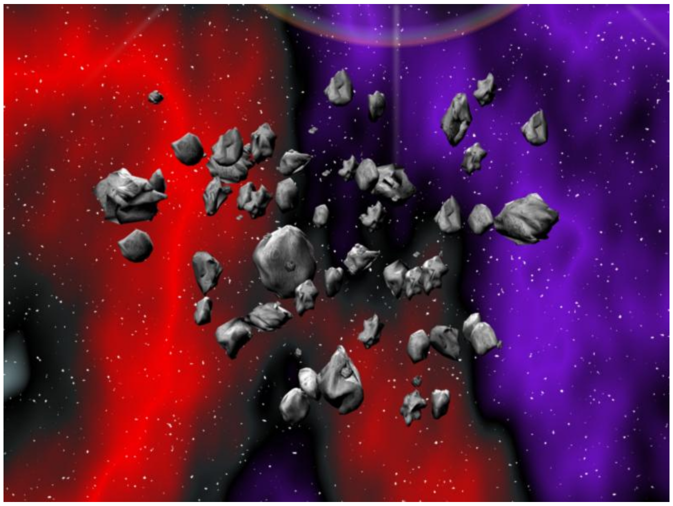

Fig. 5.11 Asteroids cloud

Fig. 5.12 Street – digital photo

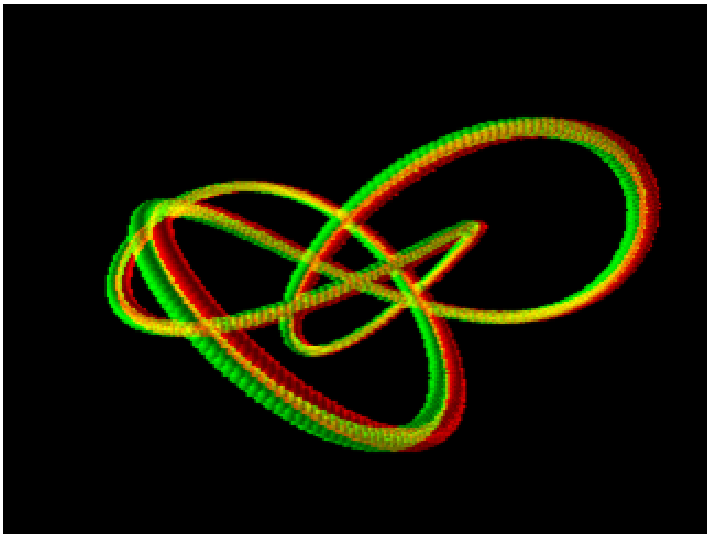

Fig. 5.14 Rotating torus knot

Fig. 5.15 Bubble matrix scene

Appendix B – CD content

experiments

- **1 – Imax**
  - survey.pdf – *survey results*
- **2 - University apparatus**
  - **1 - Static balls**
    - *Files pic. 0 – 10 for left and right views*
  - **2 - Text reading**
    - *Pictures of text (in czech) shifted from -30(shifted to left) to +30 (shifted to right)pixels*
  - **3 - Comparison of two movies**
    - *'Bad' and 'good' movie in 640x480 and 1024x768 pixel resolution with particular avisynth files*
  - **4 - Stereoscopic application**
    - stereotest - *contains both built application and source in C++.*
    - Readme.txt - *file contains a key map for users.*
    - .tri files – *selection of objects in .tri format*
- **3 – CRT**
  - **1 - Digital camera photos**
    - *Anaglyph pictures taken by digital camera.*
  - **2 - Keystoning error**
    - *Two movies of meteors in space created with converged camera axes technique.*
  - **3 - Film effects**
    - *Movie utilizing film effects.*
  - **4 - Shifted frames**
    - *Five movies containing frame shifting (from 0 to 5 frames).*
  - **5 - Non-infinite DOF**
    - *Movie utilizing non-infinite depth of field*
- **4 – Mobile** – *different anaglyph images used during tests on mobile device*
  - **1 – Bubbles**
  - **2 - Moving torus knot**

        - **3 – Room**
        - **4 - Torus magnitude changing**
        - **5 - Torus size changing**
    - **5 – Bonuses**
        - **1 – Balls**

            A set of pictures with different disparities (the same as in **University apparatus/Static balls** *folder) but with a size cue not included.*
        - **2 – Mars**

            Anaglyph pictures in two different colors.
        - **3 – Meteors**

            Movie created with converged camera axes technique.
        - **4 - Bubble matrix**

            Pictures made in a scene of 'bubble matrix'animation with camera axes converged + the animation itself (not in stereo!)

software apparatus – *free software used for this work*

- **1 - Anaglyph maker**
- **2 - AviSynth**
- **3 - Stereoscopic player**

    After Avisynth installation stereoscopic movies can be run by loading the particular .avs file into the player.

Library register

František Mikšíček, student of Faculty of Applied Sciences at the University of West Bohemia, declares to give this work to the Faculty of Applied Sciences to the effect of archiving and availability for consultations on its libraries.

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