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Vasilii Marshev

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THÈSE DE DOCTORAT DE

L'UNIVERSITÉ DE BRETAGNE OCCIDENTALE

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Biologie, Santé
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Par

Vasilii MARSHEV

Human vision and virtual reality

How virtual reality can impact the visual system and help studying it

Thèse présentée et soutenue à Brest, le 17 mai 2021

Unité de recherche : LaTIM INSERM U1101

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Dedicated to eternity.

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LIST OF ABBREVIATIONS

- AD** accommodation demand. 75, 79, 80, 82, 83, 86, 88
- AR** accommodation response. 73, 75, 78–83, 86–89, 113
- BD** blink duration. 37, 41–43, 48, 49
- BIC** Bayes Information Criterion. 102, 103, 107
- BR** blink rate. 37–39, 41–44, 48, 49
- CI** confidence interval. 38, 41–43, 46, 47
- CTPD** *difference between current test target and distractors in learning sequence.* 99–105
- DL** *average orientation of distractors in learning sequence.* 99
- DS** desktop screen. 37–40, 43, 44, 46, 48–50, 68
- FOV** field of view. 51–53, 57–60
- FPS** first person shooter. 52, 53, 58
- HMD** head mounted display. 21, 23, 24, 37–39, 43, 48–52, 57
- LLT** lipid layer thickness. 37, 45–47, 49, 50
- PTT** presentation time threshold. 11, 56, 57
- RT** reaction time. 96, 100–109
- SF** spatial frequency. 79–83, 85–89
- SSQ** Simulator Sickness Questionnaire. 39, 40, 43, 44
- TT** *target orientation in test trial.* 99, 104, 105
- UFOV** Useful Field Of Vision. 51–53, 56–59
- VE** virtual environment. 18, 22, 24, 25, 29, 51, 60, 61, 63, 65, 66, 68, 112
- VFQ** Visual Fatigue Questionnaire. 40, 43, 44
- VR** virtual reality. 15, 18, 19, 21–29, 33, 36–39, 44, 48, 50–54, 56–66, 68, 70, 78, 89, 92, 95, 112, 113, 136

INTRODUCTION

Virtual Reality (VR) refers to computer technology that simulates the physical presence of a user in a digital environment and with which the user can interact. In order to maximize the user's immersion in this new environment VR may act on different senses (visual, sound or haptic). However, due to the importance of vision in our perception of the world, VR technology first of all focuses on displays that can be basically divided into two categories : headsets or multi-projected environments (e.g. Cave Automatic Virtual Environment). If CAVEs are mainly research tools reserved to large companies and universities, recent technological advances, in particular in terms of displays and sensors, have allowed VR headsets to enter the consumer market (as of 2018, 171 million people worldwide were VR users [1]).

Although head mounted VR displays have significantly improved with time (compactness, quality of the display, etc.), the fundamental design of VR headset is very close to the first stereoscope developed by C. Wheatstone (1838) for his work on binocular vision. As a result, a number of concerns exist about the potential risks it can pose to the user's vision.

Firstly, there is a group of risks linked to behavioural and physiological consequences. Notably, because the VR headset architecture revolves around screens placed in front of the user, the usability issues of regular screens may apply to VR headsets. While there are well known concerns in regard to the negative impact of regular display use on ocular health, the risks for VR users are less known.

The second group of risks includes perceptual aftereffects that follow the VR use. VR headset presents specific viewing conditions, which require adaptation from the visual system. These potential risks concern the re-adaptation after VR session and the perceptual errors coming with it.

In the first group of risks we put the issue of user's experience. One of the most studied consequences of VR use is cybersickness, or visually induced motion sickness, which is a number of symptoms, including nausea, disorientation, headache and others, which appear during and after the VR session [2].

VR headset also presents a powerful tool for studying vision in controlled conditions. VR provides various benefits over traditional psychophysical methods to facilitate experimental research in highly controlled, yet naturalistic three-dimensional environments. VR allows for a vastly wider, compared to regular screens, spectre of possible stimulation for investigation of perception and action [3; 4].

Reciprocally, vision science can aid the development of the VR technology for better user experience and more diverse, natural and immersive virtual environment (VE). For instance, the study of discomfort brought by the accommodation-vergence conflict motivated the concept of multifocal stimulation [5; 6] to engage accommodation and vergence in

accordance with the observed stimuli and between the two. Investigation of factors of the cybersickness relating to vision allowed to propose ways to optimize the stimulation [7; 8]. And as the intensive study of stereoscopic vision brought around the rise of the VR technology, the further investigation of the psychology, neurology and physiology of vision can provide illuminating ideas to go beyond the design, principles and the purpose of VR headsets in display technologies, as well as in vision dysfunction, rehabilitation and vision restoration.

The present dissertation focuses on this relationship between VR and vision science. In Chapter 1 we present a general view of the technology and how it uses our knowledge about visual system to create immersive virtual experiences. In Chapter 2, we investigate the possible negative influence of VR use on visual system : ocular health (Section 2.2.2), visual processing (Section 2.2.3) and cybersickness (Section 2.2.4). These three experiments represent three aspects of the effect of VR on the user : physiological and behavioral aftereffects, cognitive aftereffects and user experience.

We continue (Chapter 3) by presenting a motorized haploscope that we constructed, a research instrument which allows to model the use of VR and other stereoscopic displays while enabling the independent control of different binocular presentation conditions, such as accommodation demand and vergence demand. We use this tool to study accommodative response to anisometric stimuli using an experimental procedure allowing to control for higher-level accommodation interference.

In line with using the VR headset to study vision, we then used the capability of VR headset of presenting three-dimensional and two-dimensional outlets of otherwise analogous stimuli in order to compare the processing of surface-like stimuli to stimuli varying in depth (Chapter 4).

The present thesis contributes to different areas where vision science and VR technology overlap. The results reported here can be used both to improve VR usability and our knowledge about the visual system. Finally, we propose possible directions for further studies that can be derived from our results.

HUMAN VISION AND VIRTUAL REALITY

1.1 Virtual Reality

1.1.1 History

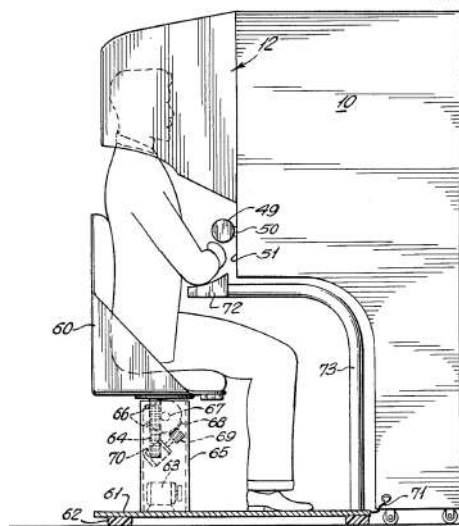


FIGURE 1.1 – *Sensorama*. Developed by Morton Heilig in 1962.

The term "virtual reality" was introduced in the eighties by Jaron Lanier [9] who later would be the founder of one of the first company selling commercial VR systems [10]. The initial idea, however, stems from Ivan Sutherland's concept of Ultimate Display [11] dating back to 1965, which was, essentially, interactive imaging system that responded to the user's actions in appropriate way in order to liken it to a synthetic reality. Yet, the first realization of VR-like device is thought to be Morton Heilig's Sensorama appearing in 1962, who is now thought to be the father of VR [10].

"Sensorama" (see Fig. 1.1) was an attraction, which presented a prerecorded sequences of synchronized multisensorial experiences [11], which included a static stereoscopic display, fans, speakers, moving chair and tubes with chemicals to invoke different senses. An important development to the initial design was head tracking that can be first found in "Headsight", an head mounted display (HMD) developed by engineers Charles Comeau and James Bryan at Philco Corporation in 1961 [10]. Its purpose was to allow specialists to view zones that could be hazardous to human remotely. User's head movements were captured with a magnetic tracking system and transmitted to the motors controlling the camera position and orientation. Another device that allowed head tracking was Sutherland's device called "The Sword of Damocles" constructed in 1968 (see Fig. 1.2), it, too, used video-streams recorded by remote cameras [11].

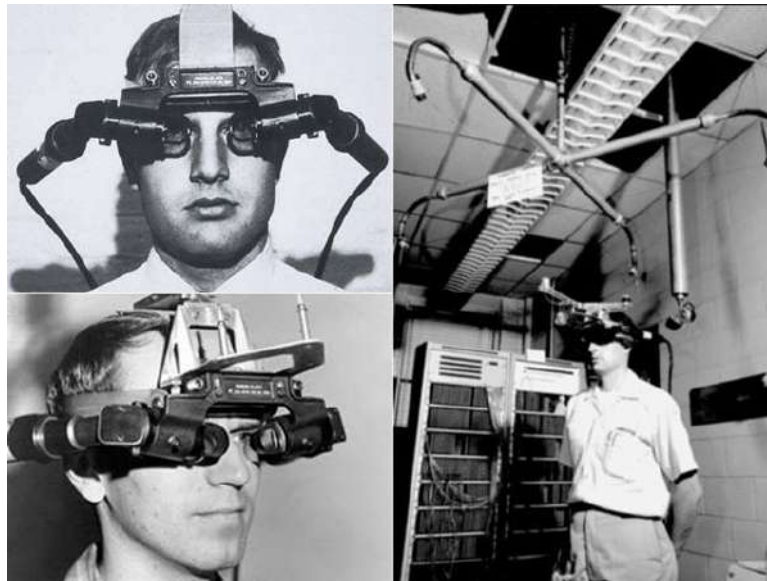


FIGURE 1.2 – *The Sword of Damocles*. Developed by Ivan Sutherland in 1968.



FIGURE 1.3 – *Visually Coupled Airborne Systems Simulator (VCASS)*. Developed by Tom Furness in 1982.

The next addition to the VR headset design was made possible thanks to development of computer graphics. Researchers and engineers were able to program the content of virtual environment. These advancements were used to develop first flight simulators. In 1982, Tom

Furness constructed Visually Coupled Airborne Systems Simulator (VCASS) (see Fig. 1.3) at the US Air Force's Armstrong Medical Research laboratories, which allowed to augment the window view with useful information, such as friend-or-foe identification, optimal flight path information and others [12]. In 1984, Mike McGreevy and Jim Humphries from NASA Ames constructed a monochrome HMD for astronaut training called Virtual Visual Environment Display (VIVED) (see Fig. 1.4). Also worth noting is Virtual Wind Tunnel developed in early 1990s at the NASA Ames which proposed novel techniques of dynamic data visualization and simulation for airflow research for aircraft development [12].



FIGURE 1.4 – *Virtual Visual Environment Display (VIVED)*. Developed by Mike McGreevy and Jim Humphries in 1984.

The next development that shaped the VR industry as we know it today was its wide adoption by entertainment, notably gaming industries, notably by Sega in 1991 and by Nintendo in 1995 [10]. However, the first system did not leave the prototype stage and production of the second was seized rather shortly after its release due to the motion sickness symptoms.

In 2001 "CAVE" was released by SAS-CUBE, which was a system of projections, trackers and 3D-glasses [10]. Even though it was an alternative to VR HMD and had advantages over its rival, headsets still comprise 75% of all virtual reality devices [13].

1.1.2 VR headset nowadays

Headset Oculus Rift and its untethered descendant Oculus Quest developed by Oculus and Valve's HTC Vive are three of the most popular models among commercially available that are on the cutting edge of the VR industry.

The architecture of a VR headset includes a corpus with adjustable straps containing two screens. The subjects view the screens through powerful lenses which allow to accommodate to the screens located so close to the eyes. Some models are equipped with a system with adjustable distance between the lenses to adapt to the user's interpupillary distance for improved comfort.

Except for head tracking done through magnetic or optical trackers [11], different input systems have been introduced. Some models are equipped with eye trackers (e.g., FOVE headset). Haptic tools include joysticks, controllers, gloves. More natural movement recognition can be attained with optic motion trackers (e.g., Microsoft Kinect) and bodysuits. Voice recognition algorithms have been introduced.

In regard to output devices, apart from stereoscopic visual stimulation, audio speakers are widely used to enrich the VE. Moving chairs and treadmills were employed to liken the feeling of movements to those projected in VR. Tools providing kinesthetic and tactile feedback were developed [11].

1.1.3 Applications

A relatively young field, VR technology developed in the age of commercialism and was shaped by the supply and demand. Thanks to this, VR benefited immensely from various fields of applications. Fuchs [9] divided the applications of VR into two groups : (i) science and technology and (ii) social sciences and life sciences. Below, we present the list of most notable applications.

Telepresence As mentioned above, the purpose of the original HMD was remote viewing. It can be necessary in hazardous conditions or in difficult to reach destinations. It can be employed for mine clearing, navigating research probes located near volcanoes, in deep ocean, in the sky or outside planet Earth. VR can also aid remote computer-supported cooperation [12].

Data visualization VR allows for visualization of complex dynamic processes in control environments for scientific and engineering applications. One of notable examples is the

Virtual Wind Tunnel mentioned above. VE can be a medium for material-free prototype testing. This is particularly useful in architecture [12; 14].

Training The synthetic nature of VE enabled training for one-of-a-kind conditions, be it preparation of routines for hazardous situations or for events that do not allow trial by error learning. These include surgery training, flight simulators, astronaut training. The feelings of immersion and presence provided by VR have been recognized as an advantage in terms of motivation and engagement of students even in conventional school, vocational and social training [15].

Psychological research VR headset offers unique capabilities to psychophysical experiments in terms of realistic three-dimensional imaging. The VR technology can provide precise control over objects' position, appearance and dynamics. It also allows to study more complex and more natural visual behaviour which involves joint eye-head movements and navigation. The immersion and realism has been recognized in the fields of educational psychology and social psychology.

Therapy The VR's capability of simulating the unlimited amount of scenarios has been recognized for, anxiety and phobia therapy [14–16], PTSD, eating and body image disorders [15]. It is specifically attractive thanks to its safety coupled with ecological validity, adaptability to any individual and increased user participation.

Entertainment A big part of the VR market is occupied by games, theatrical performances and visual art.

1.2 Human visual system

The design of the VR headset mimics the natural conditions of binocular vision to attain the impression of realistic imaging by exploiting the assumptions and expectations of the visual system. Here we present an overview of the visual system in order to provide a clearer understanding of the roots of possible risks that VR headsets can pose and possible parameters of vision that VR headsets can help study.

The visual system is a holistic representation of neural and sensory substrate and mechanisms that provide the ability to process and use optical stimulation. It includes peripheral and central parts, and ascending and descending neural pathways (Fig. 1.5).

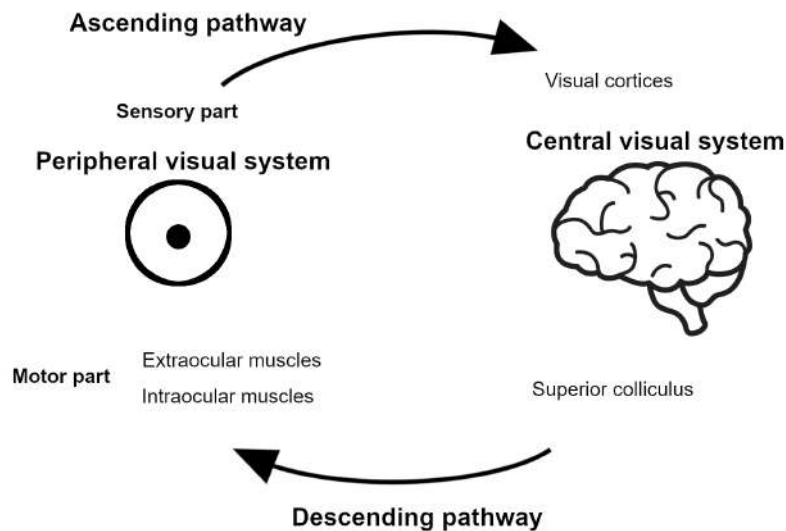


FIGURE 1.5 – **The structure of visual system** The visual system consists of peripheral visual system, ascending pathways, central visual system and descending pathways. The peripheral visual system includes the sensory part and the motor part. The motor part consists of extraocular muscles, which rotate the eye in eye socket, and intraocular muscles, which govern lens and pupil. The sensory part converts the outside world image into signal through retina. The sensory signal then travels through ascending pathway to the brain for processing. The central visual system includes areas in brain stem and cerebral cortex where visual sensory signal is processed and generates commands to the peripheral visual system. The motor signal travels through descending pathway to the motor part of the peripheral visual system.

1.2.1 Peripheral visual system

The peripheral visual system consists of the eye ball (with everything it contains) and three pairs of reciprocal extraocular muscles orienting the eye in the orbit [17]. The outer surface of the eye is covered with tear film, which protects and hydrate the eye surface and which is cleaned, reinforced and redistributed by eye lid during eye blink [18]. As the eye is the only part of the visual system exposed to the outer world, the ocular health risk is an important issue to consider in the design of the VR.

The peripheral visual system can be divided into sensory part and motor part. The sensory part is described below and the motor part is described in the section dedicated to the descending pathways (see Descending pathways).

The purpose of the sensory part of the peripheral part of the visual system is to encode the information about the projection of the world. The light passes into the eye through (a) the cornea, (b) the pupil dilated by the muscles located in the iris, which regulates the amount of light going in, (c) the transparent lens whose configuration, controlled by the ciliary muscle, changes the vergence of the light, (d) vitreous body and falls on the retina [17] (see Fig. 1.6).

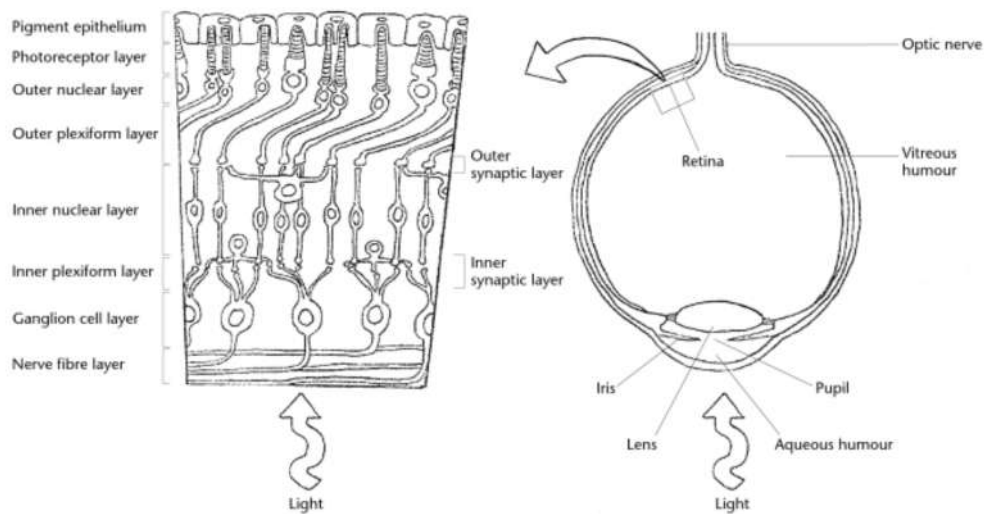


FIGURE 1.6 – *The anatomy of the peripheral part of the visual system.* The scheme of retina (on the left) demonstrates its multi-layer tightly packed structure. The scheme of the eye ball (on the right) shows the pathway of the light inside the eye and the position of the parts of the eye that light passes through before reaching the retina.

Retina is the sensory element of the eye, on which the light brings the projection of the world. Photoreceptors, distributed across the retina, if activated by the light, transmit the activation into neural and chemical signal [19]. Retina is divided into fovea (the central part with the highest receptor density), perifovea (a belt encompassing fovea), and parafovea (surrounding perifovea) [20]. Photoreceptors transfer signals to bipolar, horizontal, amacrine cells and, eventually, to ganglion cells, which effectively are sensitive to specific kind of stimuli, such as edge or movement, in a certain area of retina - receptive field [19; 20]. At this level, the screen resolution and luminosity of the VR headset have crucial impact on the user's experience.

1.2.2 Ascending pathways

By ascending pathways, neural signal travels from retina to the central nervous system. The retina ganglion cells' outputs are gathered into the ascending path of the optic nerve (Fig. 1.7). The optic nerve leads to optic chiasm located in diencephalon, a part of the forebrain, immediately under hypothalamus [22]. Here, retinotectal pathway leads smaller part of fiber to superior colliculus located in midbrain (where ascending pathways meet with descending pathways controlling eye movements) [20].

Retino-geniculo-striate pathway connects the retina and, through chiasm (where fiber coming from the nasal half of the retina goes through optic tract to the contralateral lateral

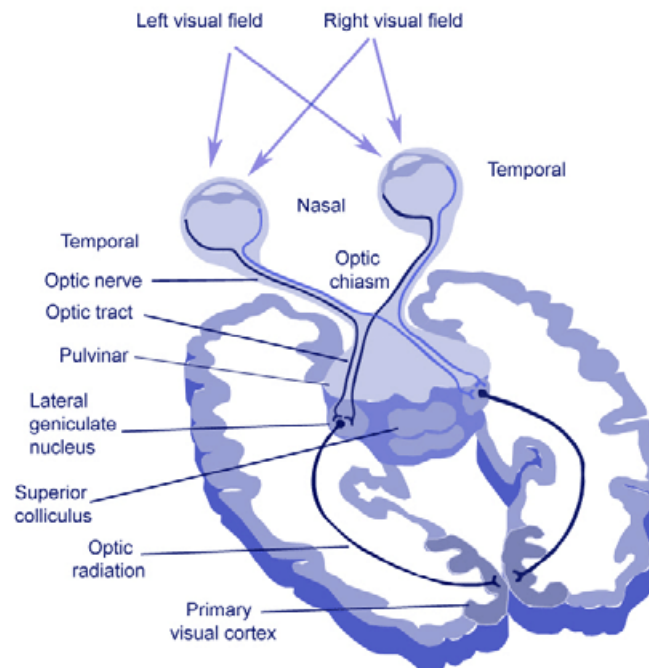


FIGURE 1.7 – *Ascending optic pathway*. From [21].

geniculate nucleus and fiber coming from the temporal half of the retina goes to the ipsilateral lateral geniculate nucleus), primary visual cortex, or striate cortex, located in occipital lobe of cerebrum where contours and movements are discerned [20].

1.2.3 Central visual system

Ascending optic pathways have topographic organisation, which means that each part of the retina projects to a set of neighbouring neurons in lateral geniculate nucleus and in striate cortex where the information from the corresponding receptive field is treated [19]. Binocular vision is provided thanks to adjacent location of neurons receiving outputs from corresponding areas of both retinæ and by specific neurons [19]. The visual system is capable of composing a single representation of the world using two retinal projections obtained from two slightly different perspectives. These perspectives, usually coming naturally from the two eyes which are slightly displaced in space, in case of VR headset are replaced either with two cameras, or, if computer generated graphics is used, by rendering two images of the same environment from two different perspectives.

Extrastriate cortex receives inputs from striate cortex and from superior colliculus and passes it to other parts of the brain [20]. Even more complex processing is possible thanks to connections to association areas (non-specific to source sensory modality), and horizontal

and vertical connections within and between visual centres that make possible interactions between modalities (e.g., for eye-hand coordination, control of the oculomotor responses, visual attention, imagination, will, memory, etc [23]. These connections are what actually make perception different from sense [17], because they allow to nest the sensual visual experience into the context, perspective and into relation with action.

The various interconnections of the visual system throughout the brain necessitates high-precision synchronization of visual stimuli with other inputs for a full sensual experience. The basic modern VR headset design solves the problem of very important coordination of head and eye movements by tracking the position and orientation of the head and updating the user's perspective into the VE. Disassociation between initiated head and eye movements, perceived proprioceptive image of head and eyes, expected sensory stimulation and perceived sensory stimulation can lead to perceptual conflict, which is believed to cause motion sickness symptoms [24]. The means of coordination with inputs to other systems, such as kinesthetic or vestibular sensations, still await their introduction to the general public.

1.2.4 Descending pathways

The descending pathways end in the motor part of the peripheral nervous system, in motor neurons whose axons are attached to extraocular and intraocular muscles [19]. The descending part of visual system can include two different things. In terms of the visual system adapted to a certain function [17], including visuo-haptic coordination, these pathways include a complex combination of pathways controlling the involved parts. However, this thesis is concerned with visual system's proper motor activity. As described above (see Peripheral visual system), there are three groups of muscles in the peripheral visual systems : iris sphincter muscle and dilator muscles controlling the iris dilation, extraocular controlling eye movements and the ciliary muscle controlling the lens. Here we will focus on the latter two groups.

Oculomotor system

There are five types of eye movements [23; 25] : saccadic eye movements for quick orientation of the fovea to the object of interest, smooth pursuit eye movements for keeping the moving object of interest in the fovea, vergence (outward and inward) eye movements to focus on objects located at different depths, vestibuloocular eye movements to compensate for head movements and optokinetic movements to compensate for the visual field movements, such as when sitting inside a moving vehicle. While same extraocular muscles are used for

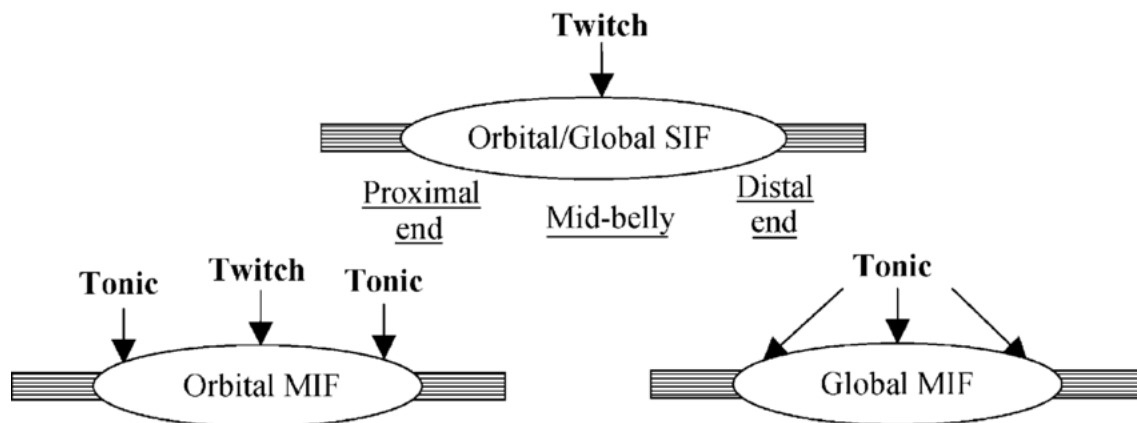


FIGURE 1.8 – *Single innervated and multiply innervated fibres of extraocular muscles.* From [27].

all types of movements, and they have single motor control centre in the brainstem [19; 25], different brain areas are involved in their production and programming [25]. The part of the nervous system that is responsible for eye movements is called oculomotor system [23].

Superior colliculus is a part of midbrain that receives both ascending and descending inputs along the visual pathways [23; 25]. These connections provide complex visual behavior.

- Connections with signals from sensory pathways from other modalities allow for rapid localization of stimuli from other modalities and eye movements toward them [23]. This is possible thanks to the map of the world constructed in superior colliculus, on which the stimuli from other modalities are mapped, as well as eye movement vectors necessary to focus on them [25].
- The connections with premotor structures allow for head movements to complete gaze movements [23].
- Interpolation with vestibular pathways allow for vestibulo-ocular reflex and optokinetic reflex to stabilize image [26].
- Volitional eye movements and cognitive control over eye movements are provided by the interactions of superior colliculus with frontal lobe, particularly, with frontal eye fields [23; 25].
- Task-related functions, such as attention, working memory, planning action sequences, are thought to be provided by input from parietal cortices [23; 25]. Connections with subcortical nuclei establish mediation and tonic control [23].

As an important part of the oculomotor system, superior colliculus integrates the oculomotor signals [25] and sends them to extraocular muscles through oculomotor, trochlear

and abducens nerves [23; 28]. These descending pathways target two types of muscle fibers through corresponding motor neurons : single innervated fibre and multiply innervated fibre [27–29]. Thanks to these two different types of muscle fiber, fast and precise eye movements are possible. They are responsible to different ocular reactions [27–29] (see Fig. 1.8).

- Single innervated fibre is controlled by twitch motor units which produces contractions based on all-or-none principle. Multiply innervated fibers are fatigue-resistant muscles producing slow movements that contract in gradual manner under tonic influence from non-twitch motor units.
- The multiply innervated fibre is also thought to produce proprioceptive afferent pathways which participate in gaze holding, eye alignment and vergence movements

The two types of motor neurons receive different types of inputs : some pathways innervate both, others innervate one or the other type [28]. This illustrates the multiple control sources and contradicts with the final common pathway hypothesis [26; 28].

Near triad

Near triad is a set of yoked reactions in the eyes whose purpose is a clear binocular projection of an object of interest [30; 31]. These reactions happen in three groups of muscles : pupillary (responsible for dilation), oculomotor (vergence) and ciliary (accommodation). While the activity of pupillary muscles is beyond the scope of the present thesis, vergence movements and accommodation are described below.

Vergence While normally both eyes move in the same direction, disjunctive eye movements occur when eyes move in opposite directions, either inward (convergence) or outward (vergence), in order to focus on an object that is located closer or further than a current fixation point in three-dimensional space [23; 25]. The vergence system is controlled by disparity signal, or the relative position of the object's projection on two retinae [32].

Vergence is comprised of four components [31; 33]. (1) The tonic component is the resting state of vergence. It is influenced by continuous vergence effort (in [34] the duration of tonic effect is discussed and measured). The resting position can be measured in darkness and is called dark vergence [35]. This component corresponds to the tonic activity provided by basal ganglia. (2) The proximal component is initiated by the viewer's awareness of the distance to the object. This component is governed by the extrastriate cortex. (3) The fusional component reflects the disparity and the effort necessary to fuse on the object. Disparity information is processed in striate and extrastriate cortices. (4) Accommodative component

reflects the coordination between vergence and accommodation. Its amount depends on the accommodative effort.

Vergence, as other oculomotor movements, are controlled by extraocular muscles. Vergence eye movements consist of two components : first, a pulse-like, or transient component initiates a pre-programmed eye movement, which is then adjusted by a step-like, or sustained component [36].

Accommodation In order to keep the image on the retina clear, it is necessary to focus the incoming light. Because the air and the internal parts of the eye on the way of light have different refractive index, a large part of this focusing occurs when the light passes through cornea (two thirds, approximately 43 D [37]), but one third of the refractive potential of the eye, as well as its variability, is introduced by lens through the mechanism of accommodation [23; 37]. The lens body consists of lens fiber cells confined in lens capsule, separated from them with lens epithelium [37].

The lens hold in place by ciliary muscles with suspensory ligaments called zonules of Zinn [37] in a fashion resembling the spokes of a bicycle wheel [23]. When the muscle is relaxed, the zonules are tight, and the lens is spread resulting in low refraction state. When muscles contract, zonules curl and the lens assumes a more round configuration increasing its refraction power [23; 37].

Ciliary ganglion, which controls ciliary muscle, receives the input from Edinger–Westphal nucleus in brainstem through oculomotor nerve [28; 38]. While this parasympathetic innervation is considered the main input, there is evidence for sympathetic contribution from brainstem [39–41] which participates in ciliary muscle relaxation [42].

There are four components in accommodation corresponding to those in vergence [31; 43]. (1) tonic component (studied and measured by [34]), (2) proximal component, (3) reflex component, the response to the change in the vergence of the light, or blur stimulus [30; 32], and (4) convergence component that reflects the influence of the vergence response on accommodation.

Accommodation-vergence conflict While normally accommodation and vergence stimuli and responses are coupled, in stereoscopic displays this coupling is compromised, because while disparity manipulation is available, the physical distance to the screens rests the same [44]. The discordance between accommodation and vergence causes visual discomfort, eye strain and visual fatigue [44; 45]. Also, vergence and accommodation responses take less time when they are coupled compared to when they are not [44]. Accommodation-vergence

conflict has important implications to the VR user's experience. Some authors proposed solutions to this issue [46].

1.3 Conclusion

In this chapter, we described the visual system, the VR headset architecture and its functioning in relation to vision. Further on, in the present thesis, we explore the dual relation between VR and vision science, which represents our knowledge about vision. This duality will be studied in two aspects : how vision science can contribute to the development of VR industry and how VR can be used to study vision.

The VR technology benefited from applying the current knowledge about the visual system for designing immersive and captivating virtual experiences which are employed in vocation, education and leisure. As the growing VR industry produces new models and concepts, the study of ergonomics, usability and potential risks can solidify and orient the development of the industry. There is considerable amount of empirical data which served to improve the technology and user experience, but the field develops, and there is still much to unfold. In the next chapter, we present three studies which help understand how VR headset impact the visual system in order to prevent possible risks.

The first study investigates the potential risks to the ocular health of VR user. While, in fact, VR can employ various senses (the effect on which is studied extensively, as well), the stimulation itself is predominantly visual, and the eye is the most exposed to the possible ill-effects of VR and, therefore, it is necessary to ensure that the growing public of VR users receives proper instructions for VR headset use. In our experiments, we studied the impact of VR use on blinking which has a substantial effect on ocular health.

In the second experiment, we study the effect of VR on perception. As can be seen above, vision is an intricate system with different cognitive functions involved. And we need to make sure that the specific viewing conditions of VR do not impact human vision as to alter perception or action, since even small alterations can have a detrimental effect on complex activities, such as driving or navigation. There is a corpus of studies attempting to establish possible influence of VR on visual processing, for instance, on depth perception [47] or proprioception [48]. In our study, we investigate the effect of adaptation to smaller field of view present in VR headsets on spatial attention spread.

The third issue discussed in the next chapter relates to much better studied field of discomfort induced by VR, called cybersickness or visually induced motion sickness. As mentioned in this chapter, it has been a concern for a long time, and the situation has been

improved considerably thanks to studies attempting to find the factors causing it, but still persists today for a number of individuals. In our third experiment, we attempted to develop a questionnaire in order to identify those more predisposed to experience cybersickness.

HEALTH RISKS FROM USING VIRTUAL REALITY HEADSETS

2.1 Introduction

In this chapter we present three experiments contributing to our knowledge of VR use-induced aftereffects on user. These three experiments represent three aspects of the effect of VR on the user : physiological and behavioral aftereffects, cognitive aftereffects and user experience. Such a wide range of research problems presented an interesting opportunity to discover various aspects of the influence of VR on visual system.

Different physiological and behavioral aftereffects have been studied previously [49–51]. Because the present thesis focuses on the visual system, in the first study (Section 2.2.2) we chose to investigate the effect of VR on ocular health. It focuses on an understudied effect of VR on blinking activity and ocular tear film state. Because this is an important issue in regular screens usability, we addressed the concern of the same issue appearing in VR users. This study was possible thanks to collaboration between Optics department of IMT Atlantique and Institute of Research and Technology bcom.com.

The second experiment (Section 2.2.3) estimates the aftereffects of VR use on spatial attention. The purpose of this experiment was to research the consequences of adaptation of the visual system to the specific viewing conditions in VR headset. Of all possible parameters that could suffer from VR use, we chose visual attention spread, because this allowed to use Useful Field of View test, one of tests that has been shown to be valid and repeatable.

The third study (Section 2.2.4) focuses on VR-induced discomfort which has been one of the major obstacles in the development of VR industry since the dawn of the technology. In this experiment, we attempted to compose a questionnaire to assess individual susceptibility to VR-induced discomfort. This study was made possible through collaboration between Optics department of IMT Atlantique and local oceanographic museum Océanopolis as a part of "SMARTCAVE" project.

2.2 Impact of VR headset use on eye blinking and lipid layer thickness

The results of this study have been accepted for publication at Journal Français d'Ophthalmologie.

2.2.1 Introduction

As discussed in Chapter 1, it is necessary to assess the possible implications of VR use on user's experience, comfort and health. The issue of visual comfort and ocular health have long been discussed in relation to regular computer screens, in particular their effect on blinking and eye fatigue [52; 53] and on the development of dry eye disease [18] ("a common condition that carries significant patient morbidity and healthcare cost" [54]). Several studies have shown that observers exposed to the regular prolonged use of desktop screens become more susceptible to dry eye and computer vision syndromes, which may originate from regular reduction of blink frequency when using desktop screen [55]. In a recent study, Kim et al. [56] found that blink rate (BR) decreased during two minutes long session when using a VR HMD when compared to using a desktop screen.

BR is, however, a parameter that shows significant dependency on environmental and individual characteristics [52; 53]. For instance, while some studies observed increasing BR with the time spent on a task, which can be a measure of fatigue [53; 57; 58], others invalidated this effect [59]. Contradictory results have also been reported with respect to the influence of mental load (Stern and Skelly [58] reported a decrease in blink frequency but not Yamada [60]) or task difficulty (decreased blink frequency reported by Stern and Skelly [58], whereas not by Cho et al. [61]). For this reason, in this study, the goal of the first experiment was to compare the potential change in BR when using VR HMD to the one observed with a conventional desktop screen as a reference, as well as BR and BD change over 20 minutes of use. The performed measures also included questionnaires to take into account the potential effect of cybersickness and eye fatigue. The details and results of the first experiment are described in Experiment 1 section. In addition, because blinking and dry eye condition are tightly linked to the tear film state [18; 62] and particularly the most superficial layer of the tear film, i.e. the lipid layer [63; 64], the goal of the second experiment was to measure lipid layer thickness (LLT) before and after a session of either VR HMD or desktop screen (DS) use. The associated methods and results are presented in Experiment 2 section.

2.2.2 Experiment 1

The goal of the first experiment was to assess the difference in blinking activity between two presentation methods : DS (referred to as desktop condition) and VR HMD (referred to as helmet condition). While stimuli were designed to be as similar as possible in both conditions, several important aspects remained different due to peculiarities of the presentation methods : 1) ambient illumination (while in desktop condition, participants were seated in a dark room, in helmet condition, the stimuli were presented on a black background), 2) screen distance (see below), 3) image resolution (see below).

Methods

Apparatus The headset used in the study was FOVE helmet (FOVE, Inc., frame rate 70 Hz, resolution 1280×1440 each, field of view 90-100°). FOVE integrates two cameras for eye tracking (70 Hz), which is a relatively novel feature for VR HMD devices. The DS was the display unit of the Tobii TX300 eye tracker (frame rate 60 Hz, resolution 1920×1080, distance 60 cm, field of view 41.5°). Room temperature, humidity and lighting conditions, remained constant during the experiment. The HMD luminance and the DS luminance were adjusted to be as similar as possible (21.33 cd/m² in the helmet condition and 23 cd/m² in the desktop condition). When using FOVE, the pupillary distance was not adjusted for each participant, as this feature was unavailable with this headset.

Participants The required sample size was calculated using G*Power3 software [65] for rmANOVA. In the experiment, one group sample went through two conditions (the helmet and the desktop conditions) giving one two-level factor. Type I error value was set to 0.05 and type II error value was set to 0.9. Effect size index was obtained from the study by Freudenthaler et al. who compared the blink frequency in two conditions : general conversation and visual display unit use [62]. The calculated value of effect size index of Cohen's d of 0,997 corresponded to effect size index Cohen's f of 0.516. Other studies showing the dependence of BR on various parameters produced even higher effect size estimates. Given the above mentioned values, 13 subjects were necessary to achieve the required power. This number is also in agreement with previous studies [66; 67]. 15 subjects were recruited for the experiment (26.8 years old; 95% CI : 21.7—32 years, 6 female and 9 male). All participants had normal or corrected to normal vision and no record of cornea-related medical conditions or binocular vision issues. Participants were allowed to use their regular glasses if required. The study was carried out in accordance with the tenets of the Declaration of Helsinki. Written informed

consent was obtained from all participants.

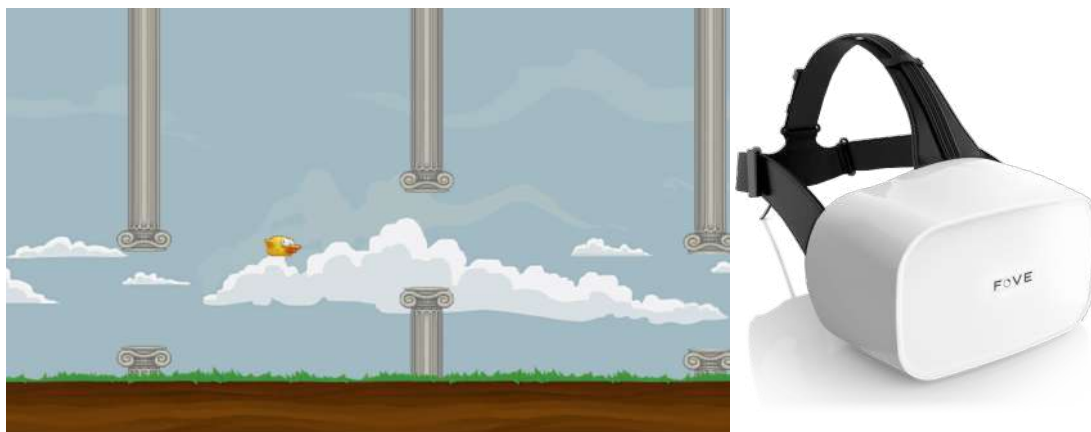


FIGURE 2.1 – *The stimuli and the VR headset used in the experiment.* Subjects played the game "Flappy Bird" (a screenshot is on the left) using a VR headset (FOVE, on the right) equipped with eye trackers which allowed to record their blinking activity.

Design and procedure The participants went through 20 minutes of playing a simplified version of the 2D game "Flappy bird" (see Fig. 2.1) in 2D, in two conditions : while wearing a headset and in front of a DS, 60 cm away. Several studies suggest that 20 minutes of use of a VR headset are sufficient to induce discomfort [68]. This duration presented a good compromise between the need for having a task long enough to possibly observe a decrease in BR, and practicalities. The choice of this game was motivated by two reasons. Firstly, it required a sustained attention. BR has been shown to reduce with effort [59], attention [69], interest [70] and in view of the relatively short experiment duration, the circumstances were organized as to facilitate BR reduction. Secondly, it would not produce any cybersickness and its simple interface and availability made it easy to implement in both conditions with limited differences.

In the helmet condition, the game was presented on a "virtual" screen on a black background. The monitor in the desktop condition was positioned at 60 cm away from the viewer, in the helmet condition, the game was presented at the same distance to ensure that the game's retinal projection was the same in both conditions. In addition, the game played on the DS was rendered at 640×480 (compared to 640×720 of each screen of the HMD) instead of the native screen resolution (1920×1080) to ensure similar pixel density per degree. Although the game ("Flappy bird") used in this study was designed to avoid any induction of cybersickness, simulator sickness questionnaire SSQ [71] was used as a further precaution. The SSQ is a list of 16 questions to evaluate three categories of symptoms : nausea related symptoms, oculo-

motor symptoms and disorientation symptoms. In addition, the questionnaire developed by Bang et al. [72] was also used to assess visual discomfort (VFQ). This questionnaire based on study by Heo et al. [73] has the advantage of being short and easy to fill out. Just before the test and right after it, the participants were seated in front of the DS while answering orally the experimenter's questions (SSQ and VFQ).

During the pretest and posttest interview, blink activity was measured using the Tobii TX300 eye tracker. When playing "Flappy bird" on the DS or the FOVE, blinking was measured respectively with the TX300 or the eye tracker integrated into the FOVE. Blinks were derived from the eye tracker data. Control for the closing percentage of the eye lid was not available with the FOVE's blink detection algorithm. Therefore, the eye closure was assumed whenever the eye tracker failed to recognize both eyes. Two criteria were used to consider absence of a pupil as a blink based on its duration : 1) bottom limit of 83 ms (following [74; 75]), in order to filter out brief data losses, 2) top limit of 1 second (one of the criteria proposed by Stern et al. [76]) to exclude other irrelevant events.

In order to limit the number of subjects and due to significant individual variability of BR in people (see Introduction and Stern et al. [52]), a within-group design was chosen. To avoid any possible influence of the order of the tests, half of the participants went through the helmet condition first, the other half were tested with the DS first. Two experimental sessions for both conditions were taken on two separate days to avoid any possible cross influence.

To assess if the blinking data from the FOVE and TX300 are in agreement, two measurements with two participants were performed to compare the counted blinks estimated by the eye trackers to those made by a human observer during two minutes playing sessions. The observer would directly watch the subject's eyes when using the TX300 or watch the videos recorded by the cameras of the FOVE's eye tracker using the FOVE debug application on a separate screen. Results (see Table 2.1) show that measurements can differ from the ones measured by an observer, and the FOVE seems somewhat less consistent with the experimenter's observations than the Tobii. Various reasons can contribute to this discrepancy in blink count, such as different proprietary algorithms. Observer's blinks and judgements about whether a blink was complete (covered the whole pupil) can affect the observer's count. Another possibility could be that the quality of the eye tracking system built in the FOVE helmet may be of poorer quality than that of the TX300, thus widening the discrepancy in the measurements made by the observer and by the FOVE eye tracker. Yet, since eye trackers based analysis has been used lately in studies dedicated to blinking activity [62; 75], this method was used to analyze blinking as well. To avoid misconclusions due to the possible bias in the eye trackers' measurements, the blink metrics measured by Tobii just before and

immediately after the game session were compared (pretest and posttest comparison).

Eye tracker	Subject	BR measured by	
		observer	eye tracker
Tobii	1	71	84
	1	71	85
	2	49	49
	2	71	85
FOVE	1	31	47
	1	49	55
	2	18	38
	2	33	15

TABLE 2.1 – *Comparison of BR measurements done by an observer and by the two eye trackers used in the study*

Analyses Each test condition (helmet and desktop conditions) consisted of three phases : pretest (included a questionnaire-based interview), test (playing the game) and posttest (included a questionnaire-based interview). In each phase of the experiment, eye blinks were recorded. Therefore, the data included two subsets : blinking activity and questionnaire results.

Blinking was analysed in two aspects : BR and blink duration (BD). Blinking during the test phase was analysed in five minutes intervals (thus, four intervals). Average number of blinks per minute was calculated for each five minute interval. Therefore, for the test, each participant's data were treated as four pairs of BR and BD averaged for each of the four five-minute intervals. Only the blinks recorded during the first two minutes were used in the analysis for the pretest and posttest interviews, as the duration of the interviews varied with participants. To compare BR in the pretest phase and the posttest phase in both conditions, the BR recorded in the pretest was subtracted from the BR recorded in the posttest. For BD analysis, average BD recorded in pretest was subtracted from that recorded in posttest.

Results

The data of three participants were excluded from the analysis, because their blink registration data were too noisy to efficiently distinguish actual blinks from data losses which occurred during the tests and resulted in eye trackers' failure to register any blinks in long time intervals, such as three consecutive minutes. BR for all participants during the game in both conditions (i.e., desktop and helmet data averaged together) was 14.9 blinks ; 95% CI :

13.5—16.2 blinks (see Table 2.2), BD was 198.8 ms; 95% CI : 195.3—202.3 ms, which is similar to what has been reported in previous studies [77].

Subject	Mean BR (Desktop/Helmet)				Mean
	0-5 minutes	5-10 minutes	10-15 minutes	15-20 minutes	
1	1.4/2.4	2.2/7	2.8/8.4	3/4.2	2.4/5.5
2	19.6/38	23.8/21.8	22/47.8	21/72.2	21.6/45
3	21/48.8	20.6/38.8	22/69.6	21/69.4	21.2/56.7
4	10.8/2.6	9.4/2.8	9.8/2.6	5.2/1.6	8.8/2.4
5	15.2/19.4	14.4/22	15.2/26	17.6/26	15.6/23.4
6	10.4/2.6	12.8/3.8	12.8/2.2	10.8/6.4	11.7/3.8
7	20.8/11.2	27.6/10.4	30.6/10	37.2/9.8	29.1/10.4
8	10.6/9.8	12.6/17.4	17.6/14.6	16.2/15.2	14.3/14.3
9	15/4.2	17.8/6.6	19.6/9.8	22/6.8	18.6/6.8
10	13/9	14/3	15.2/12	15.6/12.4	14.5/9.1
11	8.2/1	7.8/0.6	11.2/4	6.8/3	8.5/2.2
12	9.8/2.2	6.4/2	7.2/2.4	14.8/1.2	9.6/2
MeanSD	135.7/12.615.5	14.17.4/11.411.5	15.57.5/17.420.9	169.2/1925.2	14.67.4/15.118.7

TABLE 2.2 – **Mean BR.** Number of blinks per minute for 5 minutes intervals throughout the experiment for each condition and for each subject are shown

Repeated measures ANOVA was used to investigate how BR and BD varied in both conditions and with time on experiment (2 (conditions) × 4 (five-minute intervals)) during the test phase. The analysis did not show significant difference in BR (rmANOVA $F(1,11) = .01, p = .92$) between the helmet condition (15.1 blinks; 95% CI : 12.6—17.6 blinks) and the desktop condition (14.6 blinks; 95% CI : 13.6—15.7 blinks). Neither the difference in BD between the helmet condition (205.75 ms; 95% CI : 200.9—210.6 ms) and the desktop condition (202.82 ms; 95% CI : 198.2—207.5 ms) was significant (rmANOVA $F(1,11) = 4.53, p = .06$).

Both parameters increased significantly with time (rmANOVA $F(1,11) = 9.19, p = .01$ for BR, rmANOVA $F(1,11) = 6.4, p = .03$ for BD), as illustrated, respectively, in Fig. 2.2 and Fig. 2.3. To support this observation, linear mixed-effects regression analysis was performed to model BR and BD as functions of time. To account for between-subject variance, a random intercept for each participant was included. To assess the effect of time, two models were compared : one with time as a fixed effect and one without. P-values were computed using Kenward-Roger approximation; this method was chosen due to the comparatively small sample size. The models confirmed an increase in BR ($F(1,83) = 4.3, p = .04, \beta = .36$) and in BD ($F(1,83) = 13, p = .001, \beta = .35$) with time.

Pretest and posttest BR comparison (the BR in pretest subtracted from the BR in posttest) did not reveal any significant differences (rmANOVA $F(1,11) < .001, p = .98$) between the helmet condition (1.2 blinks; 95% CI : -3.5—+5.8 blinks) and the desktop condition (1.3

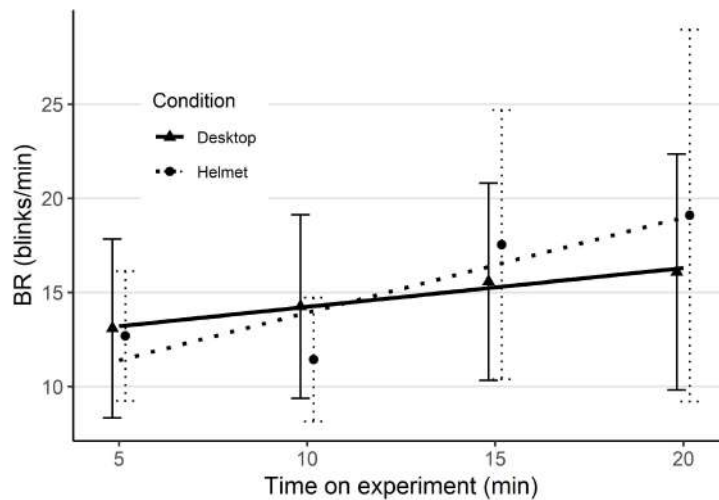


FIGURE 2.2 – **Blink rate throughout the game session in the two conditions.** Number of blinks per minute (blink rate, BR) averaged for five-minute intervals across the participants ($N = 12$) while playing a game in two conditions (while using a virtual reality headset and desktop screen) with regression lines is plotted. No significant difference between the conditions was found. Blink rate increases with time. Dots indicate mean blink rate for the previous 5 minutes across all the participants for the helmet condition, and triangles indicate blink rate for the desktop condition. The dashed and solid vertical lines represent the 95% confidence intervals for the helmet and desktop conditions, respectively. Also, linear models were fitted for the helmet (dashed) and the desktop (solid) conditions.

blinks; 95% CI : -4.2—+6.7). The comparison of BD (the BD in pretest subtracted from the BD in posttest) also did not show significant difference ($F(1,11) < .001$, $p = .92$) between the helmet condition (-4.67 ms; 95% CI : -34.8—+25.4 ms) and the desktop condition (-7.23 ms; 95% CI : -75.7—+61.2).

Regarding the questionnaires measuring eye fatigue (VFQ) and discomfort (SSQ) induced by the use of HMD or DS, the difference between the posttest and the pretest scores was calculated to compare the conditions (helmet vs desktop) using the Wilcoxon paired test. The results did not show significant differences between the conditions (helmet vs desktop) for both questionnaires (SSQ : $V = 46$, $p = .62$; VFQ : $V = 15.5$, $p = .13$, see Fig. 2.4).

In view of the absence of differences between the two conditions and the importance of individual variations in blinking (see previous sections), individual results were analyzed to see if for some of the participants BR varied more significantly than for others, depending on the test conditions (see Table 2.3). In this analysis, 20 BR values (for each minute) were taken for each participant to obtain more reliable datasets. False discovery rate correction for multiple comparisons was used. The data show that among 12 subjects, who participated in the experiment, four demonstrated significantly more blinks in the helmet condition, seven

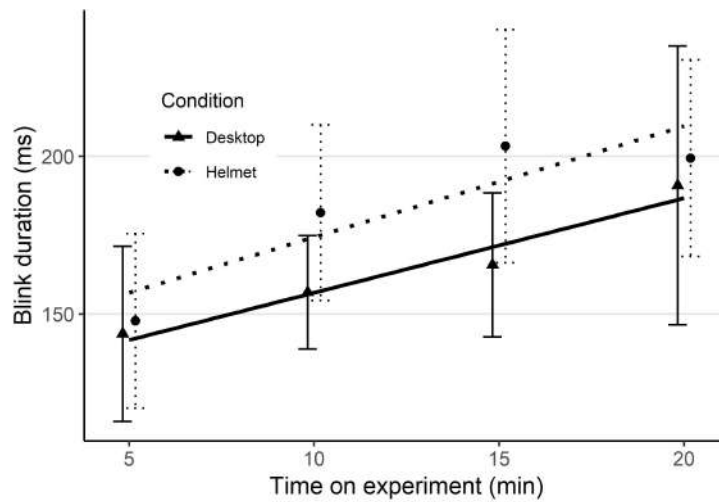


FIGURE 2.3 – **Blink duration throughout the game session in the two conditions.** The duration of blinks averaged in five-minute intervals across the participants ($N = 12$) while playing a game in two conditions (while using a virtual reality headset and desktop screen) with regression lines is plotted. No significant difference between the conditions was found. Blink duration increases with time. Ordinate : blinks duration is scaled on the ordinate axis, abscissae : time into the test. Dots indicate mean duration for the previous 5 minutes across all the participants for the helmet condition and triangles indicate blink rate for the desktop condition. The dashed and solid vertical lines represent the 95% confidence intervals for the helmet and desktop conditions, respectively. Also, linear models were fitted for the helmet (dashed line) and the desktop (solid line) conditions.

subjects showed significantly more blinks in the desktop condition, and in one participant, no significant difference was found in BR between the conditions. In order to see if questionnaire scores reflected this individual variability, questionnaire score change and BR differences were tested between the conditions for correlation with Spearman correlation coefficient. No significant correlation was found for both questionnaires (SSQ : $\rho = .29$, $p = .35$; VFQ : $\rho = -.16$, $p = .61$).

Conclusion

Experiment 1 did not show significant differences between the effects of VR headset and DS use on blinking, but found that BR gradually increased during the experiment in both conditions. In Experiment 2, we continue the comparison by directly measuring one of the parameters of the tear film state.

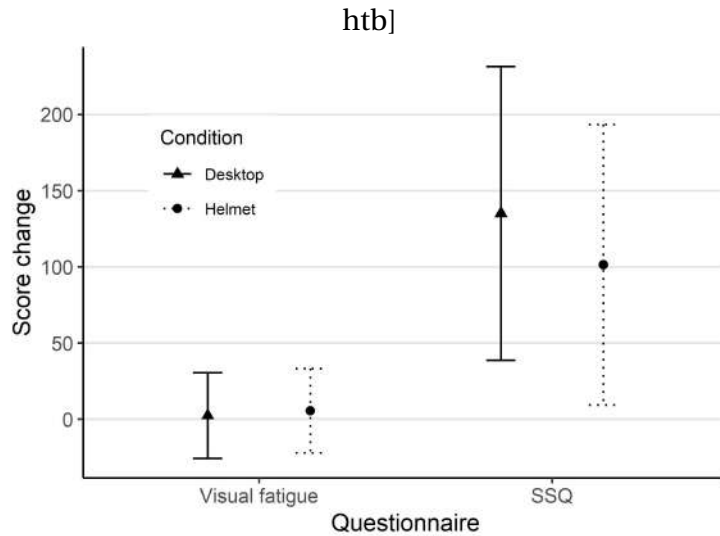


FIGURE 2.4 – **Blink rate change after the game session in the two conditions.** Average change in blink rate across all participants after 20 minutes of playing the game wearing virtual reality headset (helmet) and in in front of a desktop screen (desktop) is plotted. Blink rate change was calculated by subtracting the blink rate measured during the interview before the test from the blink rate measured after the test. No significant differences was found. The data in the helmet condition is plotted on the left and in the desktop condition on the right.

Subject	<i>F</i>	Corrected <i>P</i> (FDR)	Mean BR; 95% CI (Helmet / Desktop), blinks
1	22.11	< .001	5.5; 3.88—7.12 / 2.35; 1.8—2.9
2	16.72	< .001	45; 33.56—56.35 / 21.6; 20.09—23.11
3	64.2	< .001	56.65; 47.59—65.71 / 21.15; 19.6—22.7
4	22.15	< .001	2.4; 1.59—3.21 / 8.8; 6.08—11.52
5	18	< .001	23.35; 20.06—26.64 / 15.6; 13.92—17.28
6	63.71	< .001	3.75; 1.97—5.53 / 11.7; 10.56—12.84
7	72.21	< .001	10.35; 9.11—11.6 / 29.05; 24.91—33.19
8	< 0.0001	> .99	14.25; 11.24—17.26 / 14.25; 12.3—16.2
9	80.54	< .001	6.75; 5.1—8.4 / 18.6; 16.61—20.6
10	14.53	.001	9.1; 6.46—11.74 / 14.45; 12.52—16.39
11	100.44	< .001	2.15; 1.27—3.03 / 8.5; 7.18—9.82
12	30.62	< .001	1.95; 1.25—2.65 / 9.55; 6.88—12.23

TABLE 2.3 – **Participants-wise analysis of the difference between the conditions**

2.2.3 Experiment 2

In Experiment 2 LLT before and after a video game session was measured. The lipid layer “is the outermost layer of the tear film” [54] and its thickness has been shown to depend on blinking frequency [63] and to correlate with dry eye symptoms severity [78]. Lipid layer is

thought to slow down the tear film evaporation rate, therefore, reduced LLT or inconsistency of its spread across the cornea due to BR decrease can lead to dry eye symptoms [64]. Subjects were divided into two groups, one of which played the game wearing FOVE headset (the helmet condition) and the other played the game in front of a DS (the desktop condition).

Methods

Apparatus As in Experiment 1, FOVE helmet was used. The instrument used to assess LLT was the LipiView® ocular surface interferometer (TearScience Inc, Morrisville, NC). During the measurement, the participant is seated in front of the apparatus and places his head on a chin rest. The built-in multi-wavelength light sources emit light into the participant's eye while the built-in cameras capture a picture of the eye. The light reflected from the tear film is used to compute the light interference patterns to infer the thickness of the outmost lipid layer of the tear film [79]. Measurements which exceeded the maximum value accessible by the apparatus (100 nm) were discarded from the analysis. All the measurements were performed by the same specialist at the Brest Regional Hospital-University Centre.

Design and procedure Participants played the game “Flappy bird” for 20 minutes as described in Experiment 1. Two groups of subjects participated in this experiment. One group played the game on a DS, the other group played it wearing FOVE headset. LLT (both eyes) was measured by the same trained optometrist right before (pretest) and right after (posttest) playing the game. Only right eyes data were used in the study.

To double check the repeatability of the data provided by the apparatus, a small study was carried out with four subjects (including one author) (25.5 years old; 95% CI : 18.4—32.6 years, 3 female, 1 male) who were tested by the same observer four times during the day between 10 a.m. and 4 p.m. with two hours intervals in same conditions (same room, same lighting, with humidity and temperature controlled by an airconditioner). Data of one participant were excluded (LLT value exceeded the maximum accessible by the apparatus (100 nm)). Coefficient of repeatability was 9 nm for the left eye and 8 nm for the right eye. These results are in agreement with another study [54] which showed that “when a single observer repeated the imaging on the same day, the coefficient of repeatability was 16 nm and the 95% limits of agreement were between -11 nm and 18 nm”.

Participants The desktop group consisted of 12 subjects (including 3 authors) (31.3 years; 95% CI : 25.5—37.2 years, 6 female and 6 male). The helmet group consisted of 12 subjects (including 3 authors) (32.8 years; 95% CI : 25.9—39.7 years, 6 female and 6 male). Data of two

subjects were discarded from the helmet group due to value of LLT exceeding the maximum value measurable with LipiView (100 nm). In order to even out the sizes of the samples in the two groups, data of two randomly chosen participants in desktop group also were not included into the analysis.

The required sample size was calculated using G*Power3 software [80] for 2×2 between-within subject ANOVA. The within-subject factor was represented with the measurement stage (pretest or posttest). The between-subject factor was represented with the condition (helmet or desktop). Type I error value was set to 0.05 and type II error value was set to 0.9. In absence of studies with similar designs, methods and conditions that could be used as reference for expected effect size estimation, the effect size was considered big (Cohen's f of 0.5) due to high test-retest reliability of the used measuring technique and the precision of the apparatus. The calculated sample size necessary to find the significant interaction of the two factors was 20. It corresponds to the resulting 20 participants (10 in each condition) whose data that were analyzed.

All participants had normal or corrected to normal vision and no record of cornea-related medical conditions. Participants were allowed to use their regular glasses if required. The study was carried out in accordance with the tenets of the Declaration of Helsinki. Written informed consent was obtained from all participants.

Results

Initial LLT (before the experiment) was 57.2 nm; 95% CI : 53.3—61.1 nm and it reached 66.5 nm; 95% CI : 62.25—70.8 nm afterwards, which was a little lower than data reported previously [81] (average 89.8 nm with standard deviation 42.5). Mixed effects ANOVA was used to test the effect of the experiment phase (pretest or posttest) and condition (helmet or desktop) on LLT.

The results showed a significant interaction between phase and condition ($F(1,18) = 9.35$, $p = .02$). Further analysis revealed significant increase in LLT in both conditions (helmet : $F(1,9) = 26.18$, $p < .001$, desktop $F(1,9) = 14.22$, $p = .004$). Also, it showed comparable initial values of LLT between the conditions (pretest : $F(1,18) = 0.77$, $p = .39$) and significant difference after 20 minutes of the session (posttest : $F(1,18) = 11.03$, $p = .004$) with a higher LLT value found in the helmet condition (58.8 nm in desktop condition, 76.2 nm in helmet condition) (see Fig. 2.5).

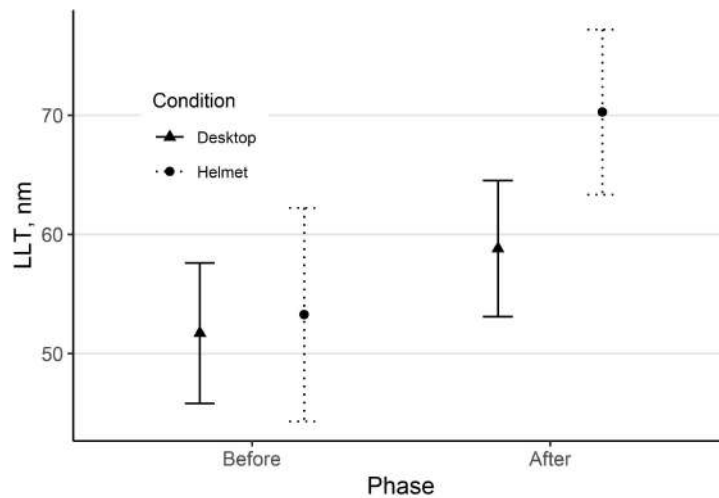


FIGURE 2.5 – **Lipid layer thickness measurements before and after the game session in the two conditions.** Lipid layer thickness averaged across all participants before and after 20 minutes of playing the game wearing virtual reality headset (helmet) and in front of a desktop screen is plotted. Lipid layer thickness increased significantly with time. Also, it increased at a higher rate with the virtual reality headset. Lipid layer thickness is scaled on the ordinate axis, the measurements done before the experiment (pretest, left) and after 20 minutes of playing the game in virtual reality headset (posttest, right). The data in the desktop condition is plotted with a solid line, and the data in the helmet condition is plotted with a dashed line.

2.2.4 Discussion

Computer vision syndrome is defined by the American Optometric Association as the combination of eye and vision problems associated with the use of computers [82]. These problems include eyestrain, tired eyes, irritation, redness, blurred vision and diplopia. One of the possible causes of computer vision syndrome is the reduction of the BR that contributes to a poor tear film quality and temporary stress of the cornea. Most studies concerning computer vision syndrome focused on the use of conventional computer screens [55] but little is known about the risk of computer vision syndrome symptoms when using VR headset. Kuze and Ukai [83] conducted a pretest-posttest questionnaire study to compare the visual fatigue effect of HMD and DS use, but their system used 3D stimuli on the contrary of this study. In the present study, the choice of the 2D stimuli instead of 3D stimuli was dictated by the need to investigate the possible outcomes of the presentation circumstances and to isolate them from the influence of 3D presentation aftereffects, such as vergence-accommodation conflict and cybersickness.

In Experiment 1, the goal was to investigate the impact of HMD use on BR, BD, cybersickness and eye strain and compared it to that of DS use. In terms of BR and BD, the present

results are in agreement with literature [53] with respect to the fact that BR and BD increase with time spent on a task. However, the change in BR and BD after the game compared to the base level (pretest-posttest comparison) was not statistically significant. In the present study, the game presentation time was comparable to other studies [83], but, perhaps, too short to allow observing a significant change in BR increase between the two conditions.

On the contrary to Kim et al. [56], the present results did not highlight any significant impact of the viewing method on BR and BD. This discrepancy may be explained by the different procedures : 1) the screen distance (0.6 m here and 1 m in the study by Kim et al. [56]), 2) the stimuli (here, participants performed a task that required them to pay attention to the scene to fulfill the task), 3) the algorithm used to count blink, and, perhaps, most of all 4) the test duration (20 minutes here and 2 minutes in Kim et al. [56]). However, the results of the present study are in agreement with Kuze and Ukai [83] who did not find differences in terms of induced eye fatigue (assessed by questionnaire scores) despite using a possibly more tiring stimulus (stereoscopic). Significant individual variations in BR between the conditions occurred in 11 of 12 subjects suggesting that personal recommendations are needed when regular use of any of the presentation techniques is considered. At the same time, according to the correlation analysis, questionnaire scores did not follow these individual variations, suggesting that questionnaires used in this study may not be sensitive enough to measure these individual susceptibilities. (The questionnaires were filled out in the first five minutes past viewing (according to Ames et al. [84]), which allowed to rule out the possibility that symptoms had dissipated by the time the subjects filled the questionnaires.)

The goal of experiment 2 was to measure the change in eye tear film LLT after DS and HMD use. According to the present results, LLT increased in both conditions, whereas no change was expected (following the results of experiment 1) or a reduction (e.g., due to reduced BR). A possible explanation would be that participants, having deprived themselves from blinking while playing, felt necessary to blink intensively after the experiment, producing excessive LLT reinforcement before the second measurement was made, as extensive blinking has been shown to cause significant increase in LLT [63].

Secondly, the experiment revealed higher degree of change of LLT after HMD use compared to DS use. In this study, the temperature and humidity conditions were not measured, but controlled by providing same environment for all participants. These environmental factors have been shown to have the influence on tear film state and, in particular, on LLT. For instance, Abusharha and colleagues [85] conducted an experiment varying the temperature in a controlled chamber and showed increase in LLT and evaporation rate as a consequence of increase of temperature. Korb et al. [86] measured the effect of humidity on LLT. They

compared the LLT in an eye in the room humidity (40-50% of relative humidity) to that in an eye isolated with goggles with 10 drops of saline added onto the mounting to increase humidity. The results [86] showed that in the eye presented with higher humidity, LLT increased significantly compared to the eye in the room humidity both during the period of different humidity and as far as 60 minutes after removing the goggles. Presumably, the isolated chamber of the HMD might preserve higher temperature and humidity because of the face skin and sweat evaporation, which might produce similar effect to that in the two studies [85; 86]. It may also be an evidence for a more apparent manifestation of a reactive mechanism protecting the ocular surface from exposure to blink reduction, however this claim would require a thorough experimental clarification.

In conclusion, the present study addressed the issue of blinking during use of VR HMD. On the contrary to a recent study [56], the present results did not show any statistically significant differences between DS and HMD in terms of blinking. However, strong individual variations were observed in all subjects but one. In view of these results, further investigation considering longer exposure time and more “natural” use (i.e. in the design used here the two conditions were as similar as possible, but in practice, VR games tend to be more visually demanding than the ones played at the DS) would be of interest, also considering additional tear film statistics [87].

2.3 Impact of VR headset on the attentional visual field

The results of this study have been presented at international conference Electronic Imaging 2021 and accepted to be published as a short paper (4 pages) with the conference proceedings.

2.3.1 Introduction

After studying one of behavioural aftereffects of VR we continued by addressing another concern in regard to the potential impact of VR HMD on the visual system, the issue of perceptual aftereffects. As the visual system adapts to the new viewing conditions, attention and other functions that serve visual perception, participate in the adaptation process, as well. Once the headset is taken off, the visual system has to readapt back to normal operation. Fatigue, as well as eye fatigue and factors connected to it, such as possible alteration in perception, ability to concentrate or focus (see [88; 89] for review) are often reported among VE aftereffects. Several studies have also investigated the impact of VR HMD on various visual performances metrics (visual acuity [90; 91], stereopsis [90; 91], oculomotor system [92; 93]). However, none to our knowledge has investigated the potential impact on the spatial extent of the attentional window.

The useful field of vision (UFOV) test is an objective measure of the attention spread [94–96]. The term was suggested in the studies made by A.F. Sanders [97; 98], who used a similar term, functional visual field, defined as “the spatial area, that has to be apprehended by the subject in performing a visual task” [97, p. 33], to refer to how far attention can reach without moving eyes towards the area of interest. Thus, a good UFOV is critical for a number of activities such as safe navigation while walking or driving. UFOV is not static and can be improved by training (e.g., see [99]) and influenced by different factors such as cognitive load [100] or mind-altering substances use [101]. A number of studies with elderly people [102–105] and patients suffering of various perception and attention disorders [106–109] have reported increase in UFOV in the participants after perception training with the use of virtual reality presentation (all these studies used UFOV test as an objective attention measure). However no studies have investigated if using a VR helmet for entertainment rather than a specific training could reduce the UFOV.

We know that the visual system can demonstrate some adaptation to changes in the allocation of attention, which is also evident from UFOV test results [110], and the field of view (FOV), in a VR HMD is, for technical reasons, strongly limited. This limited FOV could lead the user to focus on a central task, in a relatively soliciting environment, two factors

which are known to lead to a deterioration of peripheral visual performances [111]. The aim of this study was thus to assess if the use of a helmet could have an impact on the visual spatial attention spread (as measured by the UFOV test).

2.3.2 Methods

Subjects

16 participants were recruited for this study (age $M = 25.9 \pm 6.2$ years, 3 women and 13 men). Assuming an effect size (Cohen's $d = 0.8$) lower than the one reported by Bentley et al [112] between young and older subjects (Cohen's $d = 1.33$), this number allows achieving a power of 0.95. In addition this number is also similar to the sample sizes used in some other studies with UFOV test and healthy subjects [100; 101]. All had normal or corrected to normal vision. If vision correction was necessary, participants used their usual prescription glasses or contact lenses. The study was executed in agreement with the tenets of the Declaration of Helsinki.

Design and apparatus

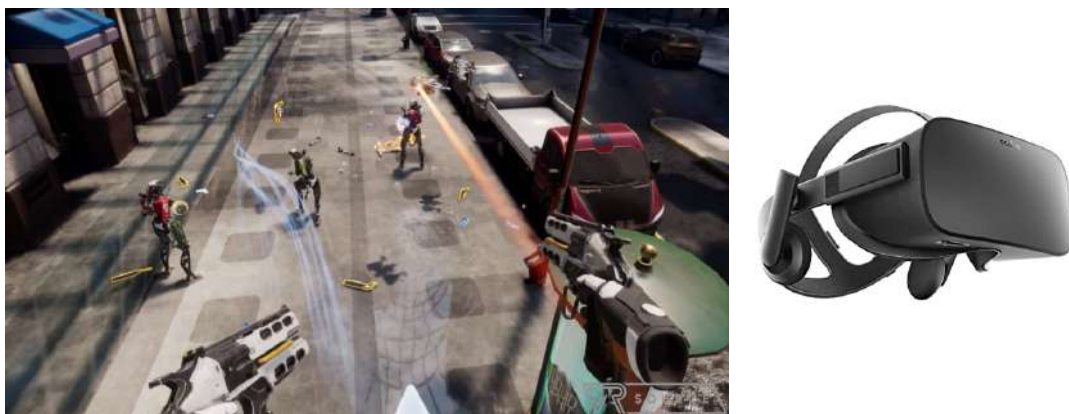


FIGURE 2.6 – *The stimuli and the VR headset used in the experiment. Subjects played the game "Robo Recall" (a screenshot is on the left) using a VR headset (Oculus Rift, on the right).*

All recruited participants were presented a virtual reality game (a first-person shooter (FPS) game "Robo Recall", Epic Games, Inc.) using the Oculus Rift VR HMD (frame rate 90 Hz, horizontal/vertical FOV : $80^\circ/90^\circ$ (throughout this paper the symbol " $^\circ$ " is used to represent the unit of angle in degree)). This game was chosen because it is highly immersive (monotonous and prolonged tasks can induce a reduction of the UFOV [113]), uses a locomotion means

that does not produce cybersickness and is freely available. Also, we wanted a game that would moderately favour central attention, and, according to El-Nasr and Yan [114], players playing FPS games tend to concentrate their eyes on the centre of the screen.

VR experience lasted for 30 minutes, which was shown to be enough to cause aftereffects attributed to VR headset use [68]. Before (pre-session) and after the game (post-session), the participants went through the UFOV test (described in the next section and summarized in Tab. 2.4).

During the UFOV test, observers are to perform two tasks : identification of a target appearing in the centre of the FOV and identification of a target appearing peripherally. This test utilizes the decreasing detection abilities of observers with three factors : 1) central task demand, 2) peripheral task demand, 3) distance between the central and peripheral targets [94; 95].

The UFOV test was administered using a desktop monitor (frame rate 60 Hz, resolution 1920×1080, distance 60 cm, 41.5°). The test consisted of three subtests which followed one by one with increasing difficulty of the task.

As part of the pre-session, participants made two training attempts, as recommended elsewhere [112]. The first subtest was excluded from the post-session in order to shorten it, since the second and the third subtests had been shown to be more sensitive to complex attention and perception alterations [115; 116]. The post-session followed immediately after the virtual environment presentation. To summarize (see Tab. 2.4), participants took the UFOV-test four times : three in the pre-VR session and one in the post-VR session. The first two UFOV tests were used for training and the third one was used as baseline.

Procedure to test the UFOV

The procedure (summarized in Tab. 2.4, Fig. 2.7) was based on the UFOV version administered with a personal computer [117]. A trial began with presentation of a black frame (7° wide and 4° high in the centre of the screen) on a light grey background (luminance = 18.2 cd/m²). After one second passed, the central task target appeared in the black frame while the peripheral target appeared 20° away from the centre of the screen. The eccentricity of the peripheral target was chosen as the average eccentricity in the original procedure [94]. This choice was also based on several pilot experiments we carried out at 10° and 30°, which were respectively too easy or too difficult, i.e., performances were out of the recordable performance efficiency range of the test. Another argument was the fact that the chosen eccentricity is close to the "eye-only range", i.e., the range of gaze shift within which the

TABLE 2.4 – **Table 1. The UFOV test procedure.** The test is divided into 11 subtests. The subtests are organised in sessions. Three sessions are taken before using the VR headset (pre-session) and one afterwards (post-session). For each subtest, the nature of the central task and peripheral task is represented.

Session	Subtest	Central task	Peripheral task
Session 1(training) distractors	1	⊕/⊗ or Nothing	⊕/⊗, without
	2	⊕ or ⊗	⊕/⊗, 7
	3	⊕⊗/⊗⊕ or ⊕⊕/⊗⊗	⊕/⊗, 23
Session 2(training) distractors	1	⊕/⊗ or Nothing	⊕/⊗, without
	2	⊕ or ⊗	⊕/⊗, 7
	3	⊕⊗/⊗⊕ or ⊕⊕/⊗⊗	⊕/⊗, 23
Session 3(pre-test) distractors	1	⊕/⊗ or Nothing	⊕/⊗, without
	2	⊕ or ⊗	⊕/⊗, 7
	3	⊕⊗/⊗⊕ or ⊕⊕/⊗⊗	⊕/⊗, 23
Session 4(post-test) distractors	2	⊕ or ⊗	⊕/⊗, 7
	3	⊕⊗/⊗⊕ or ⊕⊕/⊗⊗	⊕/⊗, 23

head moves little or does not move at all [118]. The target (either central or peripheral) was a darker grey square (side 2°, luminance = 16.2 cd/m²) either with a cross (⊗) or a plus (⊕) of light grey (luminance = 18.2 cd/m²) in the centre. The target presentation was followed by a mask consisting of 400-500 white lines 1-3 pixels wide and 10-15° long, covering the area of the presentation for one second. After that, the participants answered the questions concerning the central and the peripheral tasks consecutively using the numpad keys of a regular computer keyboard. The procedure described here above was used for each subtest. The nature of the stimuli however varied as detailed here after.

In subtest 1, the central target appeared in 50% of trials, participants are asked to indicate if there has been any. In subtest 2, the central target was either a cross or a plus sign and participants were asked to indicate which of the two had been presented. In subtest 3, two central targets appeared side by side in the black frame, and participants were asked to

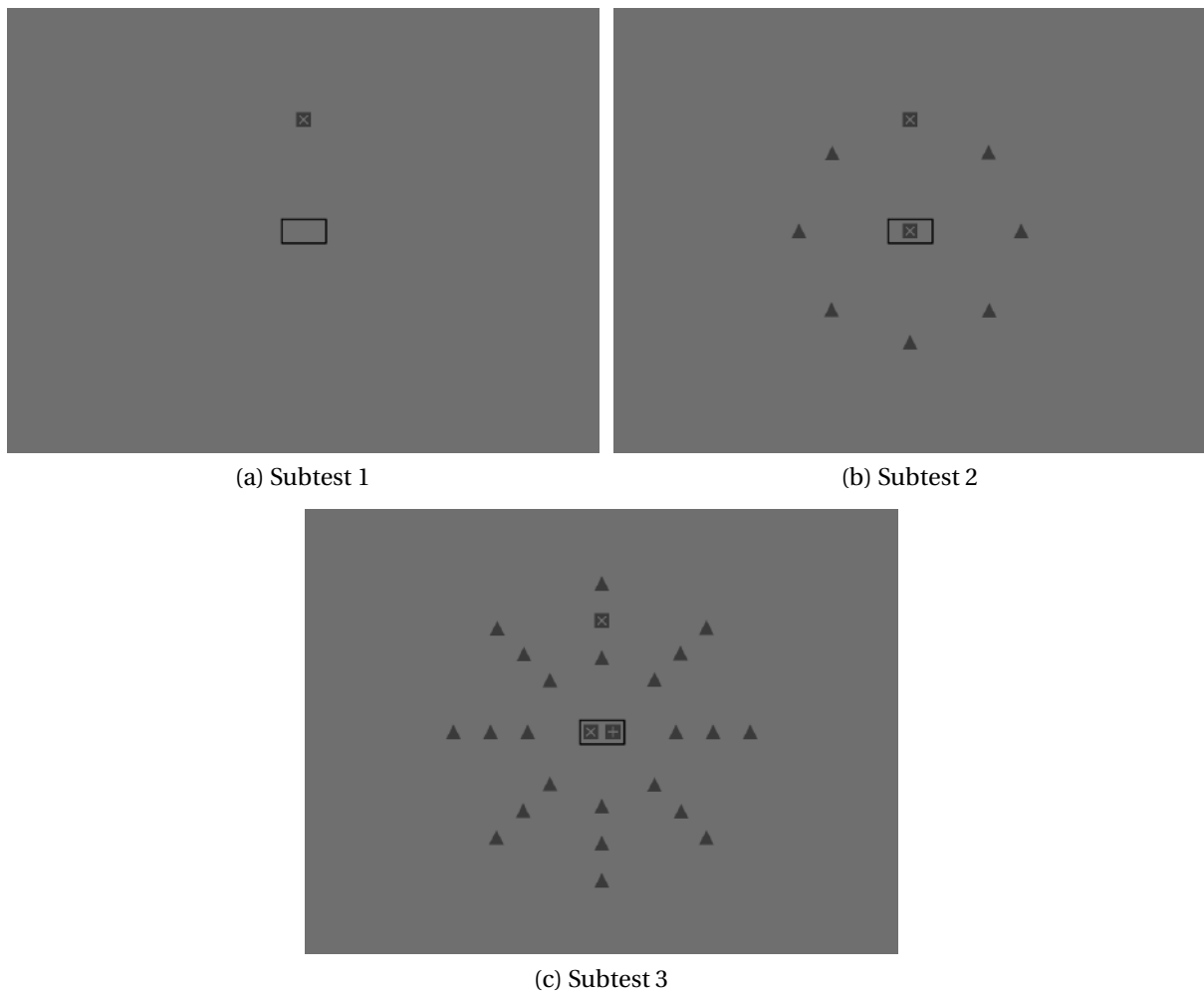


FIGURE 2.7 – **Graphical representation of stimuli for each subtest in UFOV test.** Colours and sizes do not match to how stimuli appeared to subjects for the sake of demonstration.

indicate if the targets had been same or not.

The peripheral target appeared in all trials in all subtests in one of eight positions (top, top-right, right, bottom-right, bottom, bottom-left, left, top-left) at the distance of 20° away from the centre of the screen. The peripheral task was to indicate the position of the peripheral target. For the second subtest, in addition to the target, seven distractors (grey triangles with side 1.5°) were also presented in all the possible positions of the peripheral target except the one occupied by the peripheral target. For the third task, in addition to the 7 peripheral distractors, 16 more were presented 10° and 30° away from the centre of the screen. In all tasks, participants were asked to press “0” if they did not know the answer to the question.

The presentation time was varied with double staircase method [119]. Subtests consisted of blocks of 16 trials. 8 of them were presented for the shorter period of time (“ascending

staircase”), the other 8 were presented for the longer period of time (“descending staircase”). If in 75% of a staircase trials both tasks were answered correctly, the presentation time was decreased, in the other case, presentation time was increased. Possible presentation time intervals fell between 16 ms and 240 ms with 32 ms step (7 positions in total). In the end of each block, the participant’s accuracy at answering correctly was presented to the subject.

A subtest was finished when two conditions were met : the ascending staircase presentation time had decreased at least once (or stayed at the maximum level) and the descending staircase presentation time had increased at least once (or stayed at the minimum level). For the second and the third subtests, the starting positions for the presentation time staircases were set on the basis of the previous first subtest results. The mean between the presentation times of the two staircases was used as a measurement of UFOV for a given subtest (i.e., the presentation time threshold, PTT).

2.3.3 Results

The results of participants whose PTT reached 240 ms (the maximum possible value available in the test) for any subtest in the third or fourth sessions were excluded from the data set, because they were considered to fail the test. For this reason, results of four participants were omitted from further analysis.

Our results (see Fig. 2.8) showed that the PTT changed significantly with increasing difficulty of the test (rmANOVA $F(2,22) = 65.6, p < .001$). Contrasts confirmed increasing PTT with increasing difficulty of the test (subtest 1 against subtest 2 : $t(22) = 6.6, p < .001$; and subtest 2 against subtest 3 : $t(22) = 5.2, p < .001$; means : subtest 1 : .049 s, subtest 2 : .113 s, subtest 3 : .159 s). This is in agreement with the previous studies on the original procedure [94; 95]. It demonstrates that the alterations in the original procedure made specifically for this study did not disrupt the validity and measuring abilities of the test.

The training effect in the pre-session was estimated in relation to the session number (sessions 1, 2 and 3). There was a main effect of session ($F(2,22) = 16.2, p < .001$). Contrasts showed significant decrease in PTT after the first session ($t(22) = -4.6, p < .001$; means : session 1 : .11, session 2 : .05), and no significant difference between the second and the third sessions ($t(22) = -.6, p = .57$). This provides support for the assumption that two training sessions were enough for the participants to reach the reliable level of efficiency.

The analysis of the effect of VR presentation on the UFOV test results showed that the PTT did not change significantly for subtest 2 ($F(1,11) = .7, p = .44$) nor for subtest 3 ($F(1,11) = .9, p = .38$). According to our results, the use of the VR headset did not thus lead to any attention

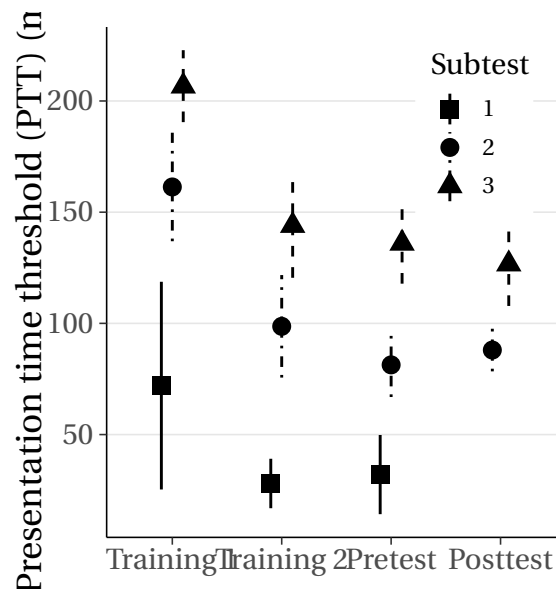


FIGURE 2.8 – **UFOV test results.** PTT for subtest 1 (circles), subtest 2 (triangles) and subtest 3 (squares). The lines indicate 95% confidence intervals for the given means. Session : 1, 2 - training, 3 - pretest, 4 - posttest. Note, that the data for subtest 1 (circles) are depicted only for first three sessions, since there was no subtest 1 in the post-session.

spread changes compared to pre-test session base level.

Within the UFOV procedure, the participant's response is considered correct only if both central and peripheral tasks are performed correctly. Spread of spatial attention might, however, manifest in differences in peripheral and central tasks accuracy. For this reason, we also analysed the participants' performances in central and peripheral tasks separately. We used correct responses ratio as the accuracy metric separately for central and peripheral tasks in each of subtests 2 and 3. Repeated measures ANOVA analysis showed a significant decrease in accuracy in central task in subtest 3 after 30 min of VR-presentation ($F(1,11) = 8.1, p = .02$), whereas in peripheral task no significant difference was found ($F(1,11) = .8, p = .39$). In subtest 2, no significant difference was found either in central task ($F(1,11) = .7, p = .41$) or in peripheral task ($F(1,11) = .4, p = .55$).

2.3.4 Discussion

Virtual environment exposure has been reported to have a long list of possible short-term aftereffects such as eye fatigue and disorientation [68]. Other studies have also shown that it could be successfully used to improve attention [105; 106]. The aim of this study was therefore to assess if the limited FOV imposed by the HMD together with a visually demanding

environment could have an impact on our attentional spread shortly after use (and therefore possible consequences on some critical activities such as driving). As an objective measure of attention, we used the UFOV test [94; 95]. The UFOV is a validated test with proven reliability [117] to assess parallel attentional processing and that can be used to predict crash risk in older drivers.

Our results did not show any significant differences between UFOV results obtained right before VR presentation and immediately after it. Separate analysis of central and peripheral tasks performances revealed, however, a significant decrease in central task in subtest 3, i.e. the most difficult of the three subtests that combine identifying central and peripheral targets among distractors. This result is relatively surprising in view of our expectations (that peripheral performances could be reduced when compared to central ones) and the literature on UFOV (usually, reported changes in UFOV correspond to similar reductions for both tasks or a decreased performances for peripheral tasks [120]). This result could first be explained by fatigue. However, the UFOV test has been shown to produce similar scores up to five consecutive sessions (number limited by the overall number of sessions undertaken in the study) with 30 minutes long pauses between the sessions [112]. Since in our study participants took breaks between the sessions if necessary, we do not expect our test reliability to differ significantly from that achieved in this study [112]. This result could also be explained as a counter-effect of the limited FOV imposed by the VR headset. After having had their visual field constrained for 30 minutes, participants allocate more attention to the periphery at the expense of the central FOV. However peripheral accuracy did not improve and we did not really deprive the peripheral visual field. Matsushita et al. [121] have shown that the size of effective visual space [122], i.e. the size in which peripheral information can be utilized, is about 80° in diameter when playing FPS which corresponds to the FOV of the VR helmet used. Another possible explanation is that the nature of the game trained the visual search skills of the participant. Several studies (e.g. [99]) have shown that games, such as FPS, can improve visual attention skills. On the other hand, such improvement usually requires a very large number of trials, much longer than our 30 minute long game, e.g. Wu et al. [123] had 10 hours of training. In addition, such improvements do not generally transfer well to a different task and if FPS has common features with classic visual search, this is not the case of the UFOV test where the presentation time is too short for a classic search and the peripheral target appears at a fixed eccentricity. What might be possible is that the UFOV sessions and the VR session trained the subject to allocate slightly more attention to peripheral stimulus, explaining why accuracy in the central task in the most difficult subtest (two targets to identify in the third subtest opposed to one in the first and second subtests)

decreased significantly.

In conclusion, our results show that the use of a commercial VR headset for 30 minutes entertainment does not present any risk in terms of UFOV reduction. The results also suggest that for better understanding of the effect of video games in a VR environment on the spread of attention across the FOV, further research may benefit from a larger sample size and, perhaps, more homogeneous task difficulty, as well as longer VR sessions.

2.4 Influence of individual parameters on cybersickness

The results of this study have been presented at international conference Electronic Imaging 2021 and accepted to be published as a short paper (4 pages) with the conference proceedings.

2.4.1 Introduction

In Sections 2.2.2 and 2.2.3 we investigated the risks posed by VR headsets in terms of dry eye syndrome and reduced FOV, as these were potentially important issues that had not been addressed before. On the contrary, the issue of personal discomfort caused by eye strain or visually induced motion sickness has received considerable interest [2; 124; 125]. However, despite recent rapid development of VR industry, this issue has not been solved and many users experience various levels of discomfort. For instance, at least a third of general population is expected to experience some symptoms of cybersickness and at least 5% to experience severe symptoms [24] that could affect their following activities along the day. (In this article, we refer to the general discomfort, motion sickness symptoms, ocular and other issues caused by VR use as cybersickness.)

A large body of literature exists on how to assess cybersickness [125] and its causes, highlighting the importance of different factors such as hardware parameters, virtual environment (VE) and individual susceptibilities (for reviews see [24; 124; 126–128]). However, despite the importance of individual factors, recommendations to protect users from being inconvenienced are still very basic (e.g. “not suitable for under 12 y.o.”, 3-levels comfort scale for games). In view of the importance of cybersickness on the use and acceptance of VR products, the aim of this study was to assess if a simple questionnaire, based on these individual factors, could be developed to allow users to self assess the risk of experiencing discomfort beforehand with better accuracy.

2.4.2 Methods

Apparatus and procedure

The VR experience used in this study was developed as a part of an interactive attraction at a scientific fair dedicated to marine wild life by local museum Océanopolis, Brest, France. This study was organized in collaboration with Océanopolis as a part of "SMARTCAVE" project, whose purpose was the development of state-of-the-art VR applications for Océanopolis.

VR sessions took place in a hall with space of 12 m² designated to the participants. Each

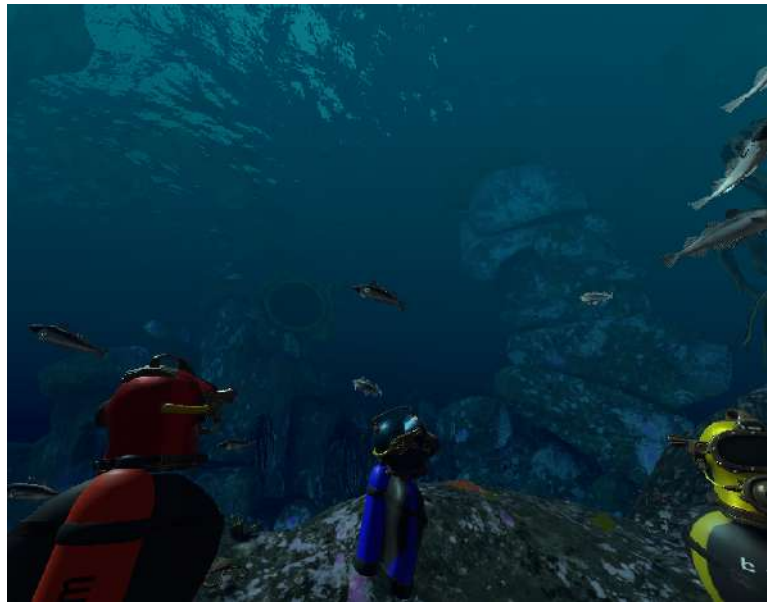


FIGURE 2.9 – *A screenshot of the virtual experience. Subjects participated in a virtual experience developed by a local museum "Océanopolis" (Brest, France).*

session took approximately 30 min. The VR sessions were administered using HTC Vive, HTC Corporation system (1080 x 1200 pixels per screen, 90 Hz, 110° field of view). The system consisted of a headset attached to a transportable computer strapped to the subject's back.

The VR experience was a sequence of scenes with teleportation-like transitions [129] between them. Scenes followed a predefined scenario and consisted of static landscape and moving imagery with occasional pointing tasks. The VE was administered for groups of four users, observers saw the avatars of other co-participants and the projection of their own hands.

The VE was presented monoscopically, parallax was the only available depth cue. Even though subjects were allowed to move freely within the designated area, very little translational motion actually was necessary and took place. No translational movement was present in the scenario. Overall, the virtual experience was rather mild. Therefore, rather low cybersickness scores were expected.

Questionnaire

The list of questions is presented below. The questionnaire was written in French. Here we present English translations. The questionnaire was divided into two groups. The first aimed to assess the predictors, and the purpose of the second group was to assess the symptoms. The first group included the questions 1-11. The answers for all 5-point Likert scale questions



FIGURE 2.10 – *The experimental setup.* Subjects could move within a 12 m² square and see three other co-participants.

were counted as 1 for extreme "Yes" and 5 for extreme "No".

(1) "Sex" - Male/Female. This question was motivated by the studies showing more severe symptoms in women, as evident from higher drop-out rate [130; 131].

(2) "Age" - Numerical. Age could be a factor, since Park et al. [131] found increased drop-out rate in older group.

(3) "Do you wear glasses?" - Yes/No, (4) "If yes, did you have to take them off to put the headset on?" - Yes/No. Uncorrected refractive error causes eye strain [132] which could be a reason for some of the symptoms of cybersickness. Also, wearing glasses inside the headset chamber would intensify interpupillary distance mismatch, which has been shown to cause cybersickness [133], since the spectacle lenses would extend closer to the centres of the headset lenses.

(5) "How many times have you used a VR headset before?" - Numerical. The purpose of this question was to assess the effect of habituation which has been demonstrated to alleviate symptoms [134; 135] (up to a point where habituation is considered the best if not the sole reliable treatment for motion sickness symptoms [136]).

(6) "Do you often have headaches or migraines?" - 5-point Likert scale. While migraine sufferers are known to be susceptible to motion sickness [136], Paroz and Potter found similarities in migraine and cybersickness triggers [137].

(7) "Are you sensitive to motion sickness (car sickness, sea sickness, etc.)?" - 5-point Likert

scale. Motion sickness history was shown to be related to higher occurrence of cybersickness [133].

(8) "Are you ill or tired?" - 5-point Likert scale. LaViola in his review [138] proposes illness and fatigue as an important individual factor.

(9) "Do you have difficulties keeping balance?" - 5-point Likert scale. This question provides an estimate of individual postural instability. Risi and Palmisano [139] found that subjects who experienced cybersickness symptoms had higher spontaneous postural activity (of centre of foot pressure) measured before the VR session. Even though Arcioni et al. [140] did not find differences in postural sway, sway area was significantly higher for those who would experience cybersickness.

(10) "Do you see well with both eyes (with or without glasses)?" - 5-point Likert scale. This question was an addition to questions (3) and (4) inquiring about possible reasons for eye strain.

(11) "Do you see well in 3D (e.g., stereograms or in 3D cinema)?" - 5-point Likert scale. This question was aimed at assessing the mismatch in binocular perception. For instance, Shibata et al. [141] found the connection between visual discomfort caused by accommodation-vergence conflict and the level of phoria and zone of clear single binocular vision. Hale and Stanney [142] expressed concerns about possibility of worse cybersickness symptoms due to oculomotor disturbances caused by mismatch in oculomotor cues.

Following four questions were introduced as measure of discomfort caused by the VR experience. However, only first three were used in formal analysis. We used the sum of their scores as a measure of presence of cybersickness symptoms.

(12) "Did this experience cause you eye discomfort or visual fatigue (dry eye sensation, etc.)?" - 5-point Likert scale.

(13) "Did this experience cause you headache or migraines?" - 5-point Likert scale.

(14) "Did this experience cause you general discomfort (nausea, dizziness, etc.)?" - 5-point Likert scale.

(15) "Did you like the experience?" - 5-point Likert scale.

Subjects

Visitors of the fair freely participated in the attraction. Immediately upon finishing a session, all subjects were approached by an experimenter and informed about an opportunity to take part in the study. After the VE, subjects could take a questionnaire form and put the filled out forms into a designated area. 224 subjects participated in the study (age $M = 30.1$,

95% CI : 27.44-32.78).

2.4.3 Results

Results of 24 subjects were discarded from further analysis due to incomplete data. Out of 195 remaining subjects, 45 reported some discomfort.

For the analysis purposes, for each subject discomfort score was calculated as the sum of questions (12)-(14) in order to use Spearman’s correlation and linear regression [143]. In order to first identify factors that had a relation to post-session VR-induced discomfort, we calculated Spearman correlation indices and significance levels (FDR correction applied) between the discomfort score and each of predictor questions (1)-(11). The correlation analysis results for the questions with scores which had significant correlation can be found in Table 2.5.

Question number and interpretation	Spearman ρ	p (FDR)
1. Higher incidence of cybersickness symptoms in women	-.19	.02
6. Higher cybersickness score in migraine sufferers	-.25	.002
7. Higher cybersickness in motion sickness sufferers	-.18	.02
8. Tired subjects tended to have higher cybersickness score	-.26	.002
11. Subjects with good stereoscopic vision were less susceptible to cybersickness	.23	.004

TABLE 2.5 – **Table 1. Correlation analysis results.** *The index and the significance of correlation between the cybersickness score and each question were calculated. Only factors with statistically significant correlations are shown. p-values are FDR-corrected*

The scores of the questions which relate to eye strain caused by uncorrected refraction error (3, 4 and 10) did not show significant correlation to the discomfort score. We also did not find any correlation with observer’s age (2). Surprisingly, correlations with previous experience of VR use (5) and posture stability (9) also did not reach insignificance.

However, the correlation analysis showed that sex (1), history of migraines (6), motion sickness (7), fatigue or illness (8) and stereoscopic vision dysfunctions self-report (11) were significantly correlated to the discomfort score (see Table 2.5).

We proceeded by building a linear regression model with cybersickness score as dependent variable and with the scores of the questions that correlated significantly with the cybersickness score as independent variables. The model was found to be significant ($F(194) = 9.19, p < .001, R^2 = .19$) and revealed only one significant factor among predictors which happened to be (8) fatigue or illness ($\beta = -.53, p < .001$). In view of the discrepancy in correlation and regression analysis results and rather low R^2 value, we performed regression assumption tests and found that residuals normality assumption was violated (Shapiro-Wilk's $W = 0.75, p < .001$). We concluded that the regression model was invalid due to the fact that the majority of subjects did not report any cybersickness symptoms.

2.4.4 Discussion

While the issue of cybersickness has not been resolved yet, different strategies were adopted in regard to virtual reality headset usability. Discomfort issues are still inherent to VR experience and continue to limit its adoption. Different strategies are implemented to reduce it and fully enjoy the promising potential of VR headsets. The main approach is, probably, hardware and software improvement, for instance reducing head tracking lag or image flicker, or using eye tracking to blur the image in the peripheral field so as to simulate a more natural vision. These developments are guided by research into the causes for individual susceptibility to cybersickness.

We are, however, still far from fully understanding the cause of cybersickness and how it can be mitigated [144] and such studies are useful to gain insights into the nature of the fundamental mechanisms causing cybersickness or to single out individuals who are at particular risk of suffering severe symptoms (see research on postural stability [139; 140]).

The present study's main goal was to develop a questionnaire which would allow predicting the level of symptoms based on a participant's responses to a short series of questions concerning their susceptibility factors.

The correlation analysis performed in this study confirmed the higher effect of VR use on women (question 1) in agreement with [130; 131; 133], on people suffering from migraines (question 6) [136; 137] and on people with history of motion sickness (question 7) [134; 135]. The analysis also showed a significant relation to fatigue or sickness (question 8) [138]. It is worth noting that the VE in our study was milder than more provocative ones employed in the majority of the studies, therefore the members of our sample who felt the symptoms are guaranteed to suffer from cybersickness in the majority of VR experiences.

A rather novel finding was the importance of stereoscopic vision issues (question 11). To

our knowledge, no studies have looked at the link between cybersickness symptoms and binocular vision issues. The discomfort could result from inefficient use of depth cues or intensified sensory conflict, e.g., between accommodation and vergence or between expected and actual movement of stimuli in depth. A possible prospect study could probe cybersickness profile peculiarities [145] emerging in different stereoscopic vision malfunctions.

We hoped that with the factors identified in correlation analysis we could define a linear model capable of accurate predictions of the chances of experiencing the discomfort. Unfortunately, as evident from the non-normal distribution of the residuals, the nature of the data did not allow for a high precision regression model. Only fatigue (question 8) appears useful as a predictor. A possible reason for this could be the low cybersickness symptom occurrence rate (22.5%) and, ultimately, mild effect of VR experience. Another explanation for significant correlations between cybersickness score and individual factors, which did not reach significance as predictors in the regression model, could point at existence of different separate mechanisms causing cybersickness symptoms. These hypothetical mechanisms could stem from different individual susceptibilities causing discomfort only to users suffering from them. For instance, subjects suffering from postural instability would experience cybersickness symptoms in VE provoking dynamic postural responses, whereas subjects with oculomotor dysfunctions would be subject to severe symptoms in VE with provoking depth cues. It would also suggest that, depending on the individual susceptibility of a given user, different mitigation techniques could be applied to a given VE for them to be the most beneficial in symptom reduction. In this regard, looking at cybersickness symptom profile differences between subjects with different susceptibilities could provide valuable information.

In terms of understanding the general mechanism causing cybersickness, given none of the questions related to the eye strain caused by refractive error showed correlation with the cybersickness score, our results provide evidence supporting the claim of lower importance of oculomotor symptoms in cybersickness [145]. However, the link between cybersickness symptoms and binocular vision issues also found in this study (question 11) allows to suppose that there are still some aspects of the oculomotor system that demand attention in respect to the development of the cybersickness symptoms. The question aiming at assessing the posture stability used in this study failed to demonstrate significant correlation, whereas objectively measured postural sway was shown to predict which subjects would feel the symptoms [139; 140]. This contradiction demonstrates the usefulness of objective measures, such as postural sway measurement for postural stability and eye movements for stereoacuity, for future applications. Even though the use of a subjective method is an obvious limitation

to our study, a portion of individual factors presumed to affect the cybersickness symptoms cannot be measured objectively and require a questionnaire. The study of cybersickness could profit from a tool assessing a wider range of possible effects both for the purpose of development of full understanding of factors in play in cybersickness and in order to prematurely identify the users who would have it worst. Such a tool would benefit from a combination of objective and subjective measures.

2.5 General conclusion

This chapter presents three studies dedicated to experimental research of risks associated with VR use and user experience. The particular risks that are discussed here originate in particular features of design of the VR headset that put the visual system in specific viewing conditions. The goal of these studies was to approach the research of the impact of VR headset use on the visual system from different sides and to capture different aspects with different methods and tools.

The first study addressed the issue of ocular health in VR users in view of existing concerns to regular display users. The results showed that the effect of VR use on blinking is comparable to that of DS. While eye tear film measurements were found to differ between VR headset and DS, the exact nature of this difference requires clarification. The results of this study were accepted for publication in *Journal Français d'Ophtalmologie*.

The second study aimed at assessing the aftereffects in visual processing caused by adaptation to specific viewing conditions of VR headset. The particular factor that was discussed here was restricted field of view. We hypothesized that the adaptation to restricted field of view could influence the distribution of attention after the VE. While we did not show significant effect of VR on attention spread, we found evidence for redistribution of attention away from the central field. The results of this study were presented and published in proceedings of international conference "Electronic Imaging 2021".

In the third study, we investigated the individual risks of experiencing discomfort associated to cybersickness on a sample of 200 subjects. The aim of the study was to develop a questionnaire to test individual susceptibilities in order to identify those who would experience severe symptoms and to understand the relative contribution of different susceptibilities to the symptoms. Our results did not allow us to refine efficiently current safety recommendations. However, our data suggest that tiredness was an important factor contributing to the development of the symptoms, and that its influence could be even more prominent than that of other factors, such as motion sickness and migraine history. This study also highlights the limitations of using strictly questionnaire methods in cybersickness symptom predictions and points at the advantages of using combined subjective and objective measures. The results of this study were presented and published in proceedings of international conference "Electronic Imaging 2021".

In the next chapter, we describe a haploscope that we constructed in the laboratory in order to use it as a model for stereoscopic displays. It can be used to study effects of unnatural binocular presentation, as well as the binocular vision itself.

BINOCULAR VISION IN VR

3.1 Construction of a motorized haploscope for vision research

3.1.1 Introduction

One of the initial goals within the present thesis was to construct a haploscope at the Optics department's laboratory to replace the one borrowed from Institut de Recherche Biomédicale des Armées (IRBA) in order to investigate binocular vision (see Fig. 3.1). Haploscope is a device designed for presenting precisely controlled stimuli separately for each eye that has, basically, the same optical design as a VR headset. It can be used both as a model for stereoscopic displays and as an experimental tool to study stereoscopic vision. It allows for a wider range of possible modalities of stimulation for the oculomotor system compared to that in VR headsets and, thus, is a powerful tool to further investigate the potential risks presented by VR displays.

The general design of our apparatus was based on that of C. Wheatstone (1838) : in front of each eye a mirror was placed through which the monocular stimulus was presented. In order to provide objective measurements of the oculomotor response, it was paired with a device for oculomotor and behavioural response measurements.



FIGURE 3.1 – *The IRBA haploscope setup. From [146].*

3.1.2 Setup structure

The haploscope consisted of an optical system for stimulus presentation managed by a computer, which also received input from behavioral data (i.e., with a joystick), and a separate

device managing the measurement of oculomotor response (autorefractometer). Below, the system is described in more detail for each element (see Fig. 3.2).

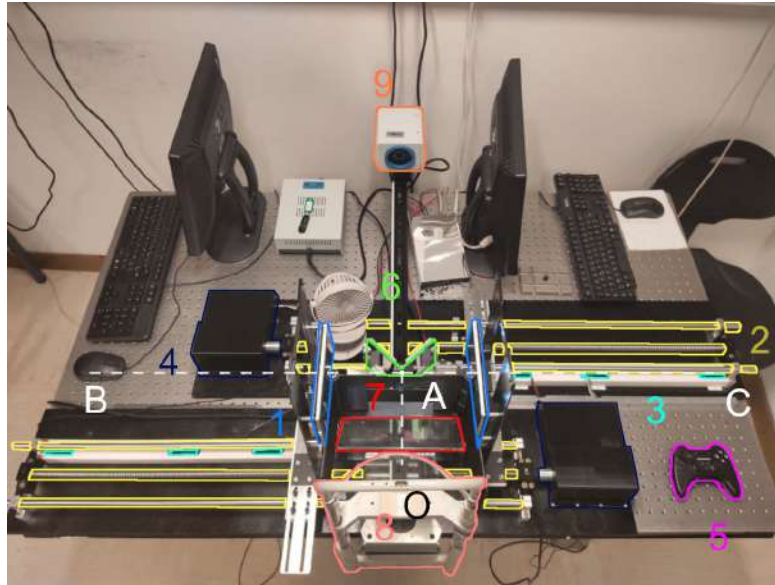


FIGURE 3.2 – **The new haploscope setup.** 1 - screens, 2 - rails (linear screw and two guides for each side), 3 - reed switch positions, 4 - caps covering motors and drivers, 5 - joystick, 6 - mirrors, 7 - beam splitter, 8 - chin rest, 9 - refractometer; O - subject's head position, A - the centre between the mirrors closest to the subject, BC - axis between the screen's centres.

Stimulus presentation

Screens Stimuli were presented on two screens (MCT070HDMI, Midas, 1024 × 600 pixels, 154 × 86 mm) (see 1 on Fig. 3.2). Each screen was fastened to a pair of vertical metallic plates using sockets drilled in the plates. The height and the orientation of the screens (vertical or horizontal) could be changed by choosing appropriate sockets. The metallic plates were positioned on a base which moved along a linear screw rail and two lateral guides (see 2 on Fig. 3.2).

Screen motorization The two sets of rails (each consisted of a screw and two guides) were positioned in parallel to each other and to the frontal axis of the observer. The rails were screwed to wooden boards attached to a workbench. The rail screw was rotated by a stepper motor powered by a driver (DM556T, Stepperonline) (both under a hood, see 4 on Fig. 3.2). The driver received the power from a transformer and commands from a microcontroller (Arduino Mega 2560, Arduino).

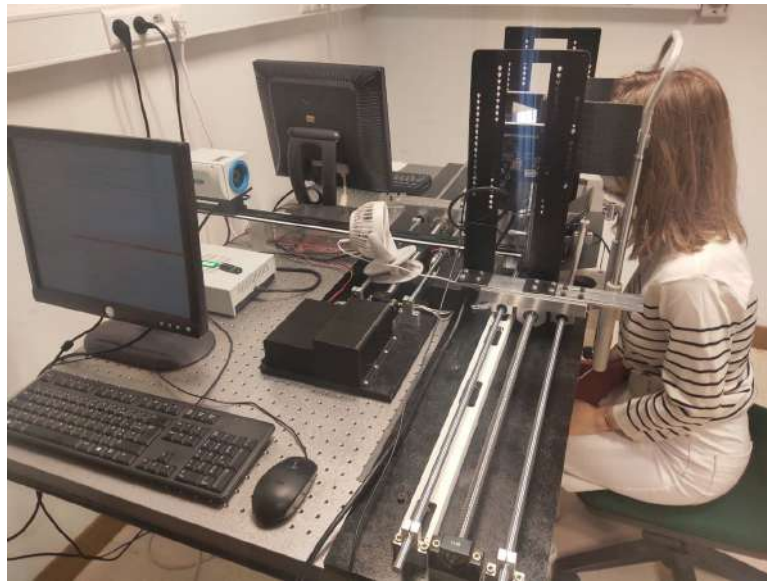


FIGURE 3.3 – *The haploscope setup with a subject. The subject sits facing the mirrors placing the chin on the chinrest.*

The microcontroller was operated by a custom C# script. As input, it received an order containing the desired positions of the screens in form of a serial data transmission. After assessing the current positions of the screens, the rotation direction necessary to reach the desired position was identified. Each motor was set into motion until the ordered position was reached.

In order to stop motors at the right moment, reed switches were placed at four positions : 4D, 3D, 2D and 1.33D (see 3 on Fig. 3.2). When the base of a screen with a magnet placed at the bottom of it passes over a switch, the reed switch closes. Reed switches are connected to microswitch inputs (Fig. 3.4). These inputs were used as signals of reaching the ordered position for stopping the motor.

Optical configuration Observers put their face on the chin rest (see 8 on Fig. 3.2) and looked at the screens through a pair of first-surface mirrors (see 6 on Fig. 3.2) rotated at 45° to the anteroposterior axis around the longitudinal axis (observer's position is shown on Fig. 3.3). The distance from the subject's face to each screen position consisted of the sum of the distance between the centre between the mirrors (see point A on Fig. 3.2) and the screen (a point on AB for the left screen or AC for the right screen on Fig. 3.2) and the distance between the subject (see point O in Fig. 3.2) and the centre between the mirrors (OA). The centres of the screens (BC) were aligned with the centre between the mirrors (see A on Fig. 3.2). The mirrors were fixed on a cylindrical base with an adjustable height platform.

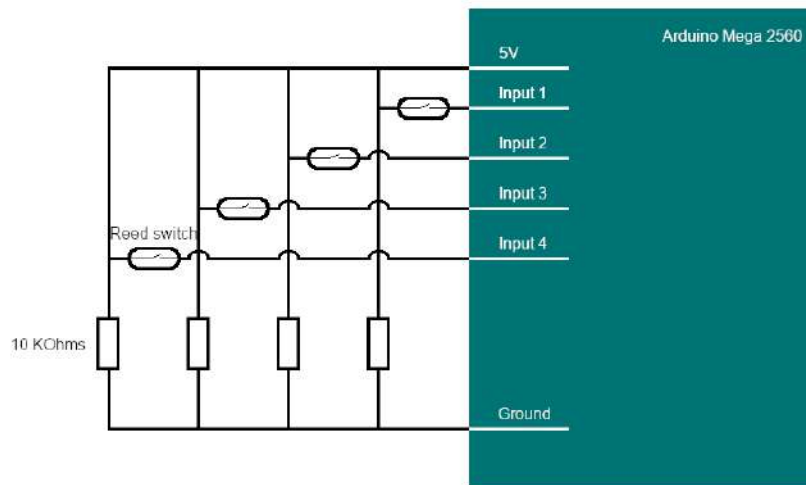


FIGURE 3.4 – **The circuit diagram for reed switches for motor control.** The green rectangle represents the multicontroller (Arduino Mega 2560). The switches were positioned under the rail at positions of 1.33 D, 2 D, 3 D and 4D from the viewer to the screen. The scheme for one motor is shown. For the other motor control, the same scheme was applied. The 5 V output was split to power both groups of switches.

Subjects viewed the mirrors through a beam splitter (see 7 on Fig. 3.2) rotated at 45° to the anteroposterior axis around the frontal axis. Under this beam splitter, parallel to it, was positioned a mirror which was aligned with a measuring device (see Fig. 3.5 and 8 on Fig. 3.2).

Response measurement

Oculomotor response The accommodation response (AR) was measured using PowerRef3 (Plusoptix) (see 8 on Fig. 3.2). This is an infrared refractometer [147] that has a series of infrared LED lights located close to the aperture of its camera. They are arranged in a configuration of several rows of LEDs, the further the row is from the aperture, the longer the row is. Thanks to this arrangement, the distribution of the light reflected from the eye allows to calculate the difference between the focal length of the eye and the actual distance between the eye and the device. This is done by the proprietary algorithm based on calibrations performed by the producer.

Essentially, the measurements that the device provides is the refraction correction necessary for the eye focal length to be equal to the distance between the aperture and the subject. Given that the distance between the subject and the aperture is 100 cm, the actual AR is calculated by subtracting the device readings from 1.

The configuration with a mirror and a beam splitter (see Fig. 3.5) allows for free viewing of stimuli during recording. The recording is performed by a dedicated computer and are

accessible after the measurement is completed. The range of measurements is between -7 and +5 D.

This device also provides eye movements recording which allows for objective absolute vergence response measurement provided that a calibration is implemented.

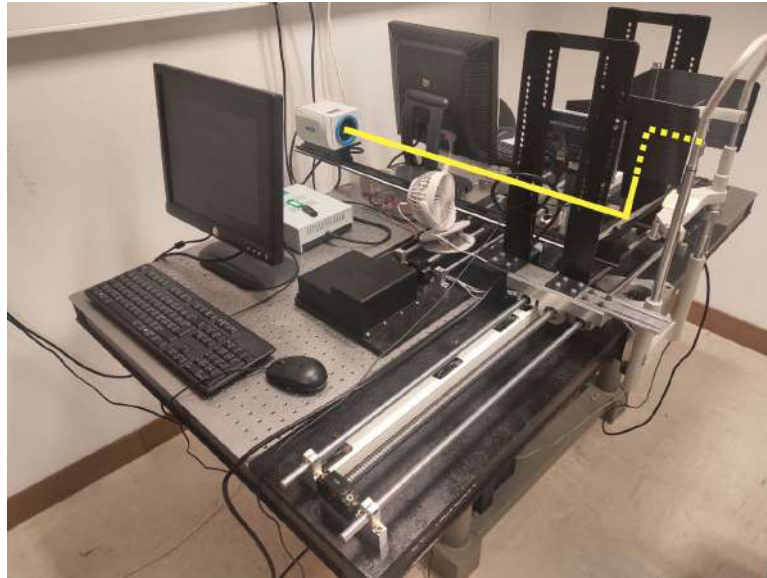


FIGURE 3.5 – **The haploscope setup.** The yellow line shows the optical path of the refractometer. The camera of the device is aligned with a mirror positioned parallel to and under a beam splitter.

Behavioural response In order to record behavioral responses, such as option choice and reaction time, a joystick was used (see 5 on Fig. 3.2).

3.1.3 Comparison to other models

A motorized haploscope brings significant advantages compared to the classic design both in terms of practicality and accessible stimulation modalities (e.g., dynamic stimuli, complex vergence and accommodation stimuli coordination). Another obvious development compared to the older models is the capability to use behavioral response to obtain more context for the recorded oculomotor response.

Vergence stimuli are often applied by rotating one haploscope arm [148] or even both arms [149; 150]. In our study, vergence stimuli could be applied by moving the stimuli along the screens. This presents an advantage in practicality (simpler control and manipulation), but also allows for fast dynamic vergence stimulus change. The screens width extended up to 34.23 degrees of visual angle at 4 D position and up to 6.61 degrees at 1.33 D position. This

limits considerably the range of vergence stimuli, but can be increased by placing bigger screens or by placing mirrors on rotating platforms. However, it was not in the focus of the present study.

Another important detail in the design of our haploscope is the use of physical distance as accommodation demand (AD). Often, lenses are used for eliciting AD. In view of the difference in AR to different ways of presenting AD (positive lenses, negative lenses) reported previously [151] and possible large optical aberrations introduced by lenses (from formal inquiry to the refractometer provider), we decided to use physical distance for AD control.

3.2 Applications

Stereoscope has been proven to be an important research instrument in regard to binocular vision [152]. For instance, thanks to the precise and independent control of different patterns of monocular visual input attained using polarized glasses set, it was made possible to distinguish individual parameters of the images that were sufficient for stereoscopic depth perception [153].

David M. Regan pioneered the research of movement in depth by describing and distinguishing different types of movements and their effect on the impression of movement in depth [154; 155]. He used a wide range of psychophysical and behavioral methods, including stereoscopic images presented monocularly to each eye [156; 157].

Another massive contribution to understanding binocular vision was made by Béla Julesz. He used the independently controlled stereo pairs of monocularly presented images consisting of random dot patterns and managed to isolate specific depth cues in order to investigate how binocular vision is represented and processed in the brain [158].

Modeling vergence and accommodation responses

At the beginning of the thesis, one of the aims motivating the construction of the haploscope was to further our understanding of the accommodation-vergence control loop. Accommodation and vergence control are attractive subjects to modeling, because both stimuli and responses can be easily measured objectively. Such models would receive the stimulus as the input and calculate the response prediction of the system as the output. Such model would be based on biologically plausible mechanisms trying to replicate the control that takes place in the actual visual system.

A crucial part of such model would be the negative feed back principle allowing to adjust

the elicited response until it corresponds to the stimulus within appropriate margins [31]. The first attempt to give a formalized description to the mechanisms of vergence-accommodation system was Westheimer's qualitative block diagram [32]. Later, first quantitative models arrived which used control theory framework, such as the vergence movements model by Toates [159] or the accommodation model by Krishnan and Stark [160]. In case of vergence models, the stimulus is image disparity, and in accommodation system, the stimulus is the amount of blur. These models used the advancements in the understanding of the neural mechanisms underlying accommodation and vergence control, for instance, by reflecting the dual dynamics character of innervation (fast movements followed by slow movements) with appropriate control sequences (phasic and tonic components).

Later models recognized the accommodation-vergence crosstalk by modeling the paired response, such as the model by Hung and Semmlow [32], and could incorporate proximal component [161].

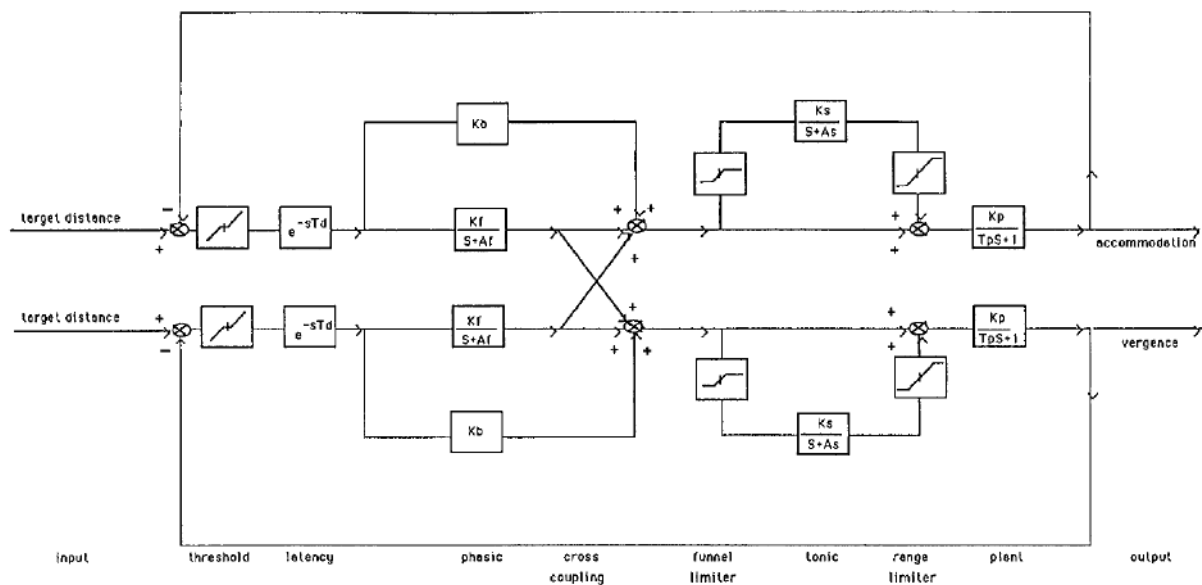


FIGURE 3.6 – *Dynamic model of cross-coupling of vergence and accommodation by Schor. From [162].*

The modern models (e.g., [161; 162], see Fig. 3.7 and 3.6) are efficient predicting the amount and the dynamics of oculomotor and accommodation responses. However, their precision depends on the values of the gains for the operators included into the model, and to this day there is no single solution for generalized values. These values are obtained based on series of controlled open-loop measurements that require isolation of different parameters of stimuli. The haploscope setup meets requirements for the majority of protocols for these

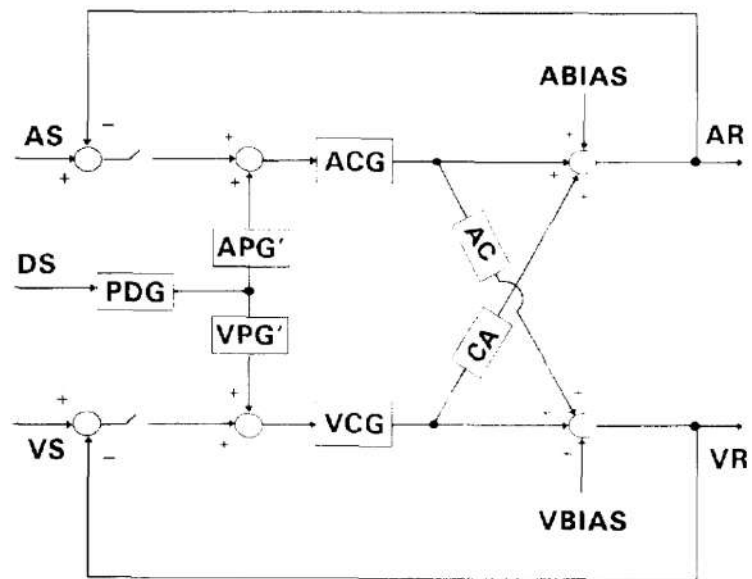


FIGURE 3.7 – *Static dual feedback model of vergence and accommodation by Hung and colleagues. From [161].*

procedures.

3.3 Accommodative response to asymmetrical accommodative stimuli

3.3.1 Introduction

Oculomotor system models usually (e.g., see above) apply a single input to the binocular system resulting in equal response in both eyes. At the same time, while asymmetrical vergence response is ubiquitous in lateral gaze, the question of asymmetrical AR (aniso-AR) has not received a definitive answer. We attempt to observe aniso-AR by controlling some of the interfering factors that could play a role in previous studies producing the conflicting results.

Fundamentally, solving the issue of the ability of the oculomotor system to demonstrate different AR in two eyes would allow to design biologically accurate models corresponding to actual innervation systems involved in accommodation.

Practically, anisometric stimuli in modern displays may appear as a design feature in monocular augmented reality models, such as Google Glass, that introduce computer-generated stimuli only for one eye. Unequal accommodation stimulation can also happen in VR headsets unintentionally due to lens-eye displacement [163]. Therefore, the reaction of the oculomotor system to anisometric stimuli is important to understanding the impact and possible risks of asymmetrical accommodation stimuli produced by such displays.

Aniso-accommodation

Marran and Schor [164] demonstrated that eyes accommodated differently proportionally to the difference in accommodative demand. In contrast, Koh and Charman [165] found that subjects kept accommodation in both eyes at the lowest of the two demands. Flitcroft et al. [166] used dynamic stimuli and suggested that the AR of the two eyes tended to approach a compromise between two demands. Vincent et al. [167] describe AR to aniso-metric stimuli as consensual with significantly higher values in the dominant eye. These different patterns of results, however, present an opposition to the single Marran and Schor's study which demonstrated precisely measured aniso-AR.

Such variety of results demonstrate the complexity of eye accommodation control (Section 1.1.2.4). Among different factors involved in eliciting AR, there are factors linked to conscious and cognitive control over accommodation through voluntary control [168; 169], and instruction and accommodative effort [170; 171]. Here, these factors will be referred to as higher level control factors [170; 171].

If we look at the methods in the studies on aniso-accommodation, we can find an important detail in the Marran and Schor's report which differed to other studies. Subjects were given unlimited training period to elicit aniso-AR. Training is known to not just influence AR, but even to elicit it in darkness [168]. We assumed that this could in fact point at the influence of higher level control in measuring aniso-AR.

In the present study we attempted to control the high level control interference expecting that if the appropriate accommodative effort and monocular feedback are provided, we would observe aniso-AR. We designed a dichoptic visual task in order to control the effect of instruction and assure appropriate feedback. Also, we used the visual task accuracy in order to filter out inefficient responses in order to assure sufficient accommodative effort and AR. Both isometropic and anisometropic stimuli were presented.

AR to spatial frequency

In order to control the level of detail of the stimulus, we chose sinusoidal gratings with maximum contrast as stimuli. In regard of spatial frequency (SF), previous studies show conflicting results as to which SF serves the best stimulus for accommodation [171].

Charman and Tucker [172] found that AR was proportional to SF. On the other hand, Owens [173] reported that AR was the highest at average SF (3-5 cpd) and dropped at high spatial frequencies. Ward [174] found insufficient accommodation to high SF (15 cpd). These results were supported more recently by Strang and colleagues [175] who measured the direction of the accommodation step change as the AD changed. They found that step response direction was more accurate in average SF (4 cpd). Lastly, Xu and colleagues [176] showed third pattern of results : i.e. that AR decreased along the SF band used in the experiment (2-16 cpd).

Lower AR to high SF has been interpreted as evidence that it constitutes a weak accommodation stimulus [173; 175], i.e. the visual system struggles to recognize blurred SF as the error signal to maintain accommodation efficiency. A different interpretation follows from a work published by Ciuffreda and Hokoda, who were able to demonstrate different patterns of the dependence of AR on SF [171]. They suggested that difference in previously published results [172; 173] was due to varying instructions : accommodation in subjects instructed to accommodate to their best ability was the highest at high SF, but in subjects instructed not to strain their eyes it was the highest in response to average SF.

The above mentioned studies lacked in their methods measures to ensure that the conditions necessary for the appropriate accommodation were met, thus allowing unbalanced higher level accommodation control effects. Because we were not able to choose the ap-

appropriate SF as accommodation stimulus based on existing literature, in our experiment SF was varied. The SF which elicits the most accurate AR would then be used for testing our aniso-accommodation hypothesis.

3.3.2 Methods

Stimuli and procedure

Subjects were seated at the motorized Wheatstone haploscope system presented in Section 3.3.1.

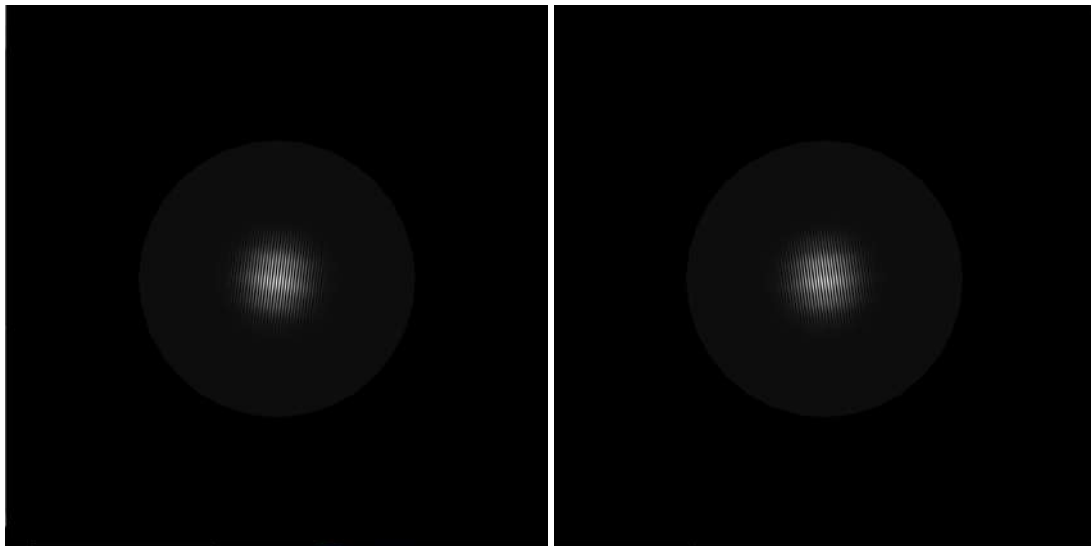


FIGURE 3.8 – **Stimuli for the experiment.** Maximum contrast sinusoidal gratings were used as stimuli. Left and right image are located side by side.

In each trial, each eye of the observer was presented with a circular sinusoidal grating (maximum 200.8 μm , minimum 6.4 μm , see Fig. 3.8) 2 deg. of v.a. in diameter in the center of the screen to be seen in the medial plane in front of the participant. The grating was placed in the centre of a dark-grey (17.7 μm) ring 9 deg. of v.a. in diameter. The ring was used as the main fusing target. Each trial was presented until the participant indicated if the orientations of the two gratings was the same or not by pressing one of two buttons on a joystick. Then a white-noise mask covered the areas of the gratings and a new trial began immediately.

Trials were grouped into blocks of 16 trials. Each block was assigned with a AD (2 and 4 D), a SF (1, 4, 10 c/deg) and an orientation difference between the gratings. Depending on the orientation difference, 15° or 30°, the orientation of a randomly chosen grating (left or right) was randomly chosen to be rotated between 5° and 10° or 25°, respectively. The

second grating orientation was shifted from it to the current block's orientation difference. This procedure ensured that the two gratings, if different, would always be oblique and on the opposite sides of the vertical axis. In a half of trials of each block the orientations of left and right gratings were same. SF and angular sizes of the two stimuli were always kept same. All possible condition combinations produced 24 blocks. The blocks' order was randomized.

Before the experiment, subjects were given the instruction and then underwent through training which included 2-4 blocks of trial (depending on each subject's wish). Subject were instructed to always keep their eyes looking straight ahead through the two mirrors. It was emphasized to them that each eye had a dedicated screen, and that they must not close one of the eyes to look at the targets sequentially or try to look at one target through one mirror. Then, after five minute long darkness adaptation, the experiment began. Participants were instructed to inform the experimenter if they felt any discomfort, and to have rest between the blocks whenever they felt necessary.

In order to eliminate vertical displacement caused by individual differences in eye position and height, which can prevent efficient fusing and cause discomfort, after the instruction subjects went through vertical displacement elimination procedure. The subject was asked to put their chin on the chin rest, the left screen was placed at 4D position and the right screen was placed at 2D position. Together with the regular grey fusing circle, in the centre of each screen a small red dot was presented. Participants were instructed to adjust the height of the chin rest until the centres of the red dots in the left and in the right stimuli were at the same level. This procedure ensured that the eyes of each subjects were at the same height as the stimuli throughout the experiment. Also, subjects were instructed to perform the same procedure after each rest pause upon putting their chin back on the chin rest.

Comparison to previous studies' methods

Previous studies that investigated AR to different spatial frequencies focused on monocular presentation of sinusoidal gratings. Accommodation measurement was performed with either a laser optometer [172; 173] or with an infrared autorefractor [175; 176]. The laser optometer technique involved observers' viewing the stimulus (the grating) and a laser speckle reflected from a rotating drum (through a beam splitter). The subjects' accommodation level was calculated from the distance of the drum at which the speckle appeared not moving which indicated that the vergence of the speckle corresponded to the eye accommodation.

Refractometers used in other studies allowed to measure average accommodation while accommodating at the target for 30 seconds [176] or one minute [175]. In the present study,

in each trial accommodation was recorded until the subjects responded. Average value was measured for each block of trials. Also, stimuli were presented dichoptically.

The target AD could be kept constant throughout the experiment (at -5 D [174] or at -2.5 D [176]), varied systematically (-1 – -7 D [172], -0.1 – -5.0 D [173]) or dynamically to register accommodation step response (1/4 D, 2/3 D [175]). For the purposes of this study, we varied target vergence (2, 4 D). Rather than using lenses, physical distance was varied.

The highest SF varied between the studies from 15 c/deg [174] to 40 c/deg [172]. In our study, SF ranges between 0.5 c/deg and up to 10 c/deg. The present highest SF is imposed by the small distance between the eyes and the screen and its density. However, since it is still considerably higher than the average band (3-5 c/deg) [173], we expect that it would be enough to elicit the response appropriate for high spatial frequencies.

As stated above, the higher level control is thought to be responsible for the striking difference in the response to high spatial frequencies among studies [171]. In the present study, we measure the subjects' efficiency in accommodating to the target by presenting them with a simple visual task. This allows us to test the hypothesis that, indeed, low AR to high frequency gratings demonstrated in some studies (e.g., [173]) is the result of inefficiency of the eye to accommodate to finer details.

Analyses

Smoothed AR measurements were used for the analysis using PowerRef 3's proprietary algorithm (the average of last 10 successful measurements). The results were calculated in R studio [177] using mixed effect model fit with subjects introduced as random intercept.

The effect of spatial frequency on accommodation response To test the hypothesis of the impact of SF on AR to isometric stimuli, mean AR of two eyes averaged across each block was used as the dependent variable. SF and AD were predictors (3×2). Only isometric blocks were included into this analysis.

Two predictions were made : (a) The visual task by itself can constitute an instruction controlling the participant's effort. Thus, high SF would elicit the highest AR. (b) Subjects' effort may need to be controlled using test accuracy. According to this prediction, after filtering out blocks with low task accuracy (<75%), thus with insufficient AR, in the remaining data set, high SF would elicit the highest AR.

Aniso-accommodation To test the aniso-accommodation hypothesis, AR difference in two eyes (smoothed right eye AR was subtracted from smoothed left eye AR) was fitted to

AD difference (-2; 0; 2). Each participant's natural anisometropia was calculated using the average difference between left and right eye AR in equidistant blocks, and then subtracted from all AR difference measurements for each participant.

Similar predictions were made. (a) The task can facilitate enough effort to elicit the aniso-AR. (b) Efficient AR filtered by removing blocks with low accuracy (<75%) can show participants' capability to aniso-accommodation.

Subjects

For the AR-SF test (3×2), the necessary sample size was calculated using repeated measures ANOVA power analysis in PANGAEA software [178]. The effect size was calculated based on data provided in Table 2 in [175, p.9], which covers accommodation responses of myope group to different spatial frequencies. Average AR and SD for SF of .5 and 4 c/deg were used to calculate Cohen's d .729.

With two replicate values (two angles between the gratings) and default variance component parameters, 13 participants were necessary to achieve the power of 0.95.

The required sample size for the aniso-accommodation hypothesis was estimated by calculation of the results of statistical analyses on simulated data based on measurements recorded in our pilot experiment and previously reported experiments [179].

Statistical analysis of the aniso-accommodation hypothesis implied one three-level factor (the anisometric stimuli, i.e. difference between left and right demands). We recorded average and SD of aniso-AR to isometric stimuli (2 and 4 D) in a pilot experiment ($N = 4$, 2 female and 2 male). Two SF values were used : 4 and 10 cpd. Participants performed the same task as described above. Resulting values were used as base level measurement for the isometric condition ($M_{iso} = -0.01$, $SD = 0.46$).

The simulation data base was composed of a series of simulated experiments. Each experiment included a number of subjects between 2 and 30. Each simulated participant isometric condition measurements consisted of six values (representing six trials) drawn from a Gaussian distribution with the average and SD indicated above. To calculate the predicted anisometric conditions measurements ($L > R$ and $L < R$), we used slope of .24 predicted according to [164] for all simulated participants ($M_{L > R} = 0.47$, $M_{L < R} = -0.49$). These data were fitted to the three conditions (iso, $L > R$, $L < R$). Each sample size was repeated in 200 experiments, thus giving a data base of 200 simulated experiments for each sample size in the range between 2 and 30 enabling us to calculate the average p-value of the test producing the power of the experiment with given predicted values on a given sample size (see Fig. 3.9).

The results of the power analysis suggested that 14 participants were needed to reach the power of .95.

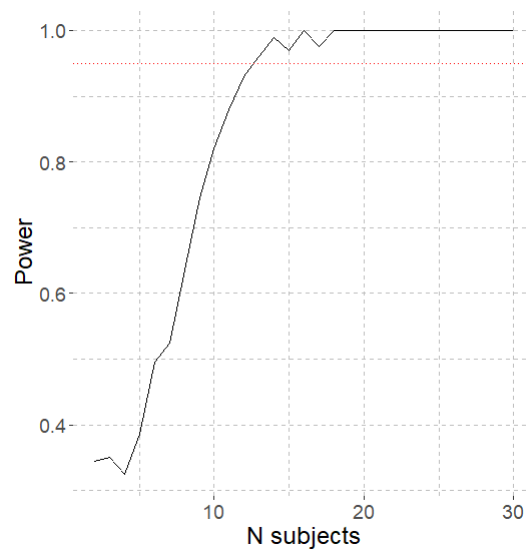


FIGURE 3.9 – *The results of power analysis using simulated experiments.* The curve represents the average *p*-value (ordinate axis) of 200 simulated experiments for a given sample size (abscissa axis). The horizontal dotted line indicates .95 power.

Out of 20 subjects recruited for the experiment (age $M = 25$, $SD = 4$, 7 females), data of 5 subjects (all male) were discarded due to poor pupil recognition performance of the refractometer, which was evident from large portions of the data containing missing accommodation recordings when stimuli were present. Subjects with prescribed correction glasses or contact lenses were asked to wear their normal correction. The study was carried out in accordance with the tenets of the Declaration of Helsinki. Written informed consent was obtained from all participants.

Results

Task accuracy

We begin by reporting the summary of the results concerning the influence of task difficulty (angle difference between left and right gratings, 15° or 30°) and accommodation demand symmetry (same or different distances) on task accuracy (see Fig. 3.10). Repeated measures ANOVA (with subjects introduced as random intercept) found a significant interaction of accommodation demand symmetry and spatial frequency ($F(2,28) = 5.19$, $p = .012$). The effect of spatial frequency was significant in isometric stimuli ($F(2,28) = 7.35$, $p = .003$)

with contrasts revealing significantly decreased accuracy only in high SF (.81) compared to low (0.89, $p = 0.009$) and average (0.89, $p = 0.006$). The contrasts in the significant effect of SF in anisometric stimuli ($F(2,28) = 16.18$, $p < .001$) showed decreasing accuracy with increasing SF (low SF : .9, average SF : .76, $p_{low\ VS\ average} = .02$; high SF : .67, $p_{average\ VS\ high} = .02$). When controlling for each SF, accuracy in anisometric stimuli was significantly lower than in isometric stimuli in average SF ($F(1,14) = 21.2$, $p < .001$, $M_{aniso} = 0.76$, $M_{iso} = 0.89$) and in high SF ($F(1,14) = 22.26$, $p < .001$, $M_{aniso} = 0.67$, $M_{iso} = 0.81$). Also, the main effect of task difficulty was found significant ($F(1,14) = 35.28$, $p < .001$, $M_{15^\circ} = 0.75$, $M_{30^\circ} = 0.87$).

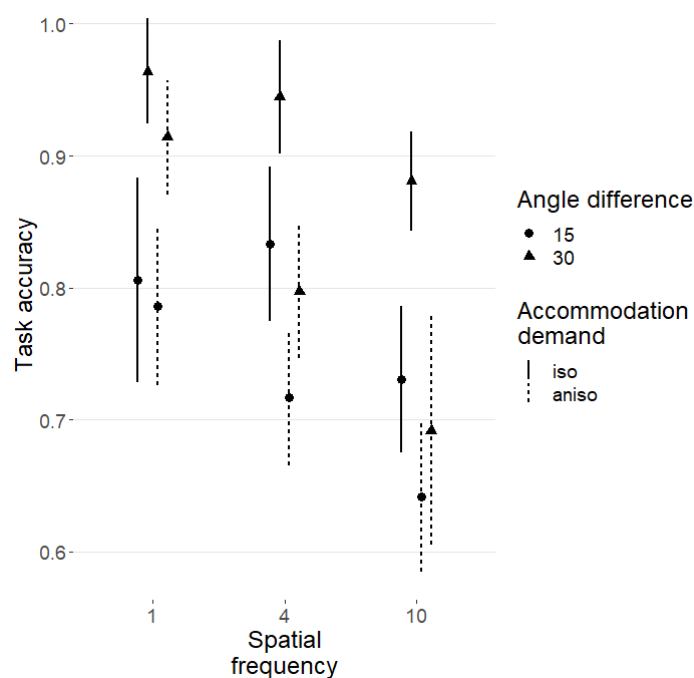


FIGURE 3.10 – *The influence of accommodation demand symmetry, stimuli spatial frequency and task difficulty on the task accuracy.* Demand symmetry is represented with the difference in distances between the subject's eyes and left and right screens. Task difficulty is represented with angle difference between gratings. Ordinate axis measures average correct response rate per block. Each data point (circles for 15° and triangles for 30° difference between left and right gratings) represents average accuracy across participants. Error bars represent 95% confidence intervals (solid lines for isometric stimuli and dashed lines for anisometric stimuli). On abscissa axis is stimulus spatial frequency. The main effects of spatial frequency, task difficulty and accommodation demand symmetry on task accuracy were found significant, as well as interaction of accommodation demand symmetry and spatial frequency (see 3.3.3.2.Results).

The results showed that task accuracy was lower when stimuli were more requiring, be it due to the smaller difference between the orientations of distances (in average and high SFs) of the two gratings or due to higher level of detail defined by SF. Therefore, the chosen test

presented considerable requirements for the visual system to resolve the stimuli. The next two sections are dedicated to the analyses of AR following the procedures described above (3.3.3.2.Analyses).

The effect of spatial frequency on accommodation response

Average AR in isometric conditions was fitted to AD and SF. The only significant factor was AD ($F(1,14) = 118.7, p < .001$) (Fig. 3.11). This contradicts to the expectations that the task presence would provide a sufficient instruction to elicit high AR to high SF.

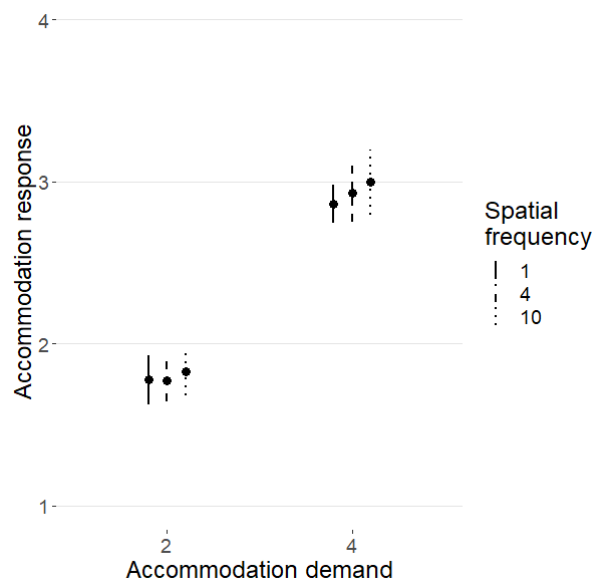


FIGURE 3.11 – *The effect of spatial frequency on accommodation response.* Abscissa represents accommodation demand (isometric stimuli only), ordinate scales the accommodation response. Line type represents spatial frequency: 1 cpd - solid line, 4 cpd - dashed line, 10 cpd - dotted line.

On the next stage we filtered out the blocks with low accuracy (<75% correct responses). Data of three subjects whose accuracy in one of the conditions did not reach 75% in at least one block were discarded. Again, the only significant factor was AD ($F(1,11) = 72.36, p < .001$). The results did not show statistically significant influence of SF on AR with or without control filtering. Therefore, the predictions of the fine-focus control hypotheses were not confirmed.

Aniso-accommodation

Because no statistically significant effect of SF on AR was found, for the following analysis, the data for all SF were pooled together. The results did not show significant effect of AD

difference on adjusted aniso-AR either before ($F(2,28) = 0.51, p = .61$), or after filtering ($F(2,26) = 0.22, p = .81$) (data of one subject were excluded from the analysis due to the absence of results in at least one condition after filtering).

3.3.3 Discussion

The goal of the present study was to measure AR to aniso-metropic stimuli while controlling for the interference from high level control over accommodation. It was done (a) by presenting a visual task requiring viewers to keep targets clear enough to perform the task, and (b) by using their task accuracy as a measure of accommodation efficiency to filter out insufficient AR which implied that the targets were not discerned correctly. In order to use the most appropriate stimulus for accommodation, we began the analysis by testing the effect of SF on AR.

The task consisted in comparison of the orientations of two Gabor gratings presented dichoptically. The procedure was applied to test two hypotheses which suppose significant effect of the factors of higher level accommodation control on AR. In the present study we aimed to provide an appropriate and objective control for the interference introduced by these factors.

The effect of spatial frequency on accommodation response

The first hypothesis tested here concerns the conflicting results in previous studies investigating AR to different SF. It was proposed by Ciuffreda and Hokoda [171] who explained the difference in results obtained in studies showing evidence for fine-focus control hypothesis (higher SF elicits higher AR) [172] and for contrast control hypothesis (average SF (3-5 cpd) elicits higher AR) [173] through the effect of instruction differences between the studies. Essentially, they argued for the fine focus control hypothesis proposing that the opposing findings were rather due to low accommodative effort in other studies.

Following this hypothesis, we expected to observe significantly different AR in different SF conditions. If this difference is found without accuracy-based filtering, it would provide evidence for fine-focus control hypothesis and establish that the chosen task and stimuli were successful in eliciting the effort necessary for appropriate AR. The significant difference between different SF found after filtering out inefficient responses would suggest that fine-focus control hypothesis is valid only for AR sufficient for the target.

Our data failed to show any dependence of AR on SF. Our results argue for the idea of SF being an inefficient accommodation stimuli. Despite not being able to see the targets

clearly (to correctly identify the targets' orientations), subjects could not adjust their accommodation for more detailed stimuli (as fine-focus control hypothesis would predict). The accommodation system also did not seize the opportunity to maximize contrast information at the SF optimal for contrast detection (as contrast control hypothesis would suggest) [171].

At the same time, subjects' task accuracy decreased with increasing SF. In previous studies in monocular presentation no difference of orientation discrimination were found [180] and small decrease was found in binocular presentation [181]. We do not consider it the result of suppression caused by binocular rivalry, because the reversals themselves would be an apparent cue for unequal orientations in the gratings, and in verbal examinations subjects reported that binocular fusion went seamlessly.

Task accuracy variation with SF implies that higher SF did, in fact, pose higher requirements for the visual system, but could not be resolved efficiently. We argue that the reason for this was inability to keep the images clear. It also allows to rule out the possible critique of 10 cpd not being high enough, since the value chosen in this study for purely technical reasons (the screen quality and pixel density) had a significant effect on task performance.

Note that a defocused sinusoidal grating could be an ambiguous stimulus for a cognitive optical system, because the gradient of the lines' contrast cannot be resolved to a sharp edge despite possible attempts of accommodation adjustment. Essentially, this opens the accommodation loop increasing the impact of voluntary control over AR and considerably decreasing the effect of actual stimulus optical qualities, which could account for the results inconsistency between previous studies.

Aniso-accommodation

The second question we asked in this study was if the aniso-AR could be demonstrated by controlling higher level accommodation control factors. The task itself was intended to require subjects to provide enough accommodative effort in order to see the targets. And using accuracy-based filtering we made sure that subjects, indeed, were able to see both targets clearly enough to perform the task. In the preliminary instruction and training it was stressed to the subjects that it was necessary not to attend to the targets sequentially, but keep them clear at the same time. In the present study we were not able to find any significant difference in aniso-AR level between different aniso-AD conditions.

An important difference in the design of the present study to that of Marran and Schor [164] was the absence of a training period dedicated to obtaining aniso-AR response prior to the experiment. We assumed that thanks to the training, subjects in Marran and Schor's

study were able to produce more consistent aniso-AR, which was not found in other studies which argued against aniso-AR. We expected that by filtering out AR which led to incorrect responses, we would obtain the data set where aniso-AR would be consistent enough to show significant differences. However, we did not observe aniso-AR to anisometropic stimuli.

From the methods of the study of Marran and Schor [164] it is difficult to claim with confidence that during the training period subjects did not learn to exhibit aniso-AR in feed-forward fashion, as it was demonstrated in experiments with voluntary control over accommodation even in absence of stimuli [168; 169]. And while Marran and Schor certainly demonstrated the actual capability of human accommodation system to show different refraction power in two eyes, the present study aimed at investigation of accommodation as a closed loop function initiated by accommodation stimulus, functional in nature.

Another apparent issue complicating interpreting the lack of dependency of aniso-AR on anisometropic stimulation was revealed in analysis of the effect of SF on AR which showed that SF did not present a strong stimulus for accommodation. It was also supported by the evidence of decreasing task accuracy with increasing SF in anisometropic conditions, which implies that while increasing SF did diminish the discernibility of stimuli, it did not function as appropriate stimulus for blur recognition operator.

3.3.4 Conclusion

VR headsets can introduce anisometropic stimuli in various ways [163]. The aim of the present study was to measure AR to anisometropic stimuli. In agreement with [165–167], we did not observe aniso-AR even when higher level accommodation control factors were controlled. Our results suggest that anisometropic stimulus presentation does not allow for efficient joint processing of both stimuli and, therefore, should be avoided.

According to our results, sinusoidal gratings used as stimuli may not be the best stimulus for eliciting appropriate accommodation response, and thus other results may be found with other stimuli. However, we believe that further research attempting to elicit aniso-AR should involve a procedure requiring appropriate accommodation (similar to our method), since this would ensure that response is stimulus-driven and not governed in feed-forward fashion.

This study also allowed to demonstrate the haploscope functionality. It will be used in the context of M. Drouot's PhD to investigate how augmented reality display could potentially destabilise binocular vision.

VR AS A VISION RESEARCH TOOL : ARE VISUAL ENSEMBLES SUPERFICIAL ?

4.1 Introduction

As stated in the Introduction, the VR headset architecture is based on a specific design that can lead to unnatural viewing conditions. In Chapter 2, we studied some of the associated risks for the visual system. We also constructed a research instrument to better study the oculomotor system and binocular vision in relation to the development of VR and augmented reality displays (Chapter 3). In this chapter we explore another side of the relation between VR and vision science, namely how VR can be used to study vision.

VR is a powerful tool for studying binocular vision in a controlled environment. Different media offer similar advantages, for instance, 3D screens have been used for studying stereoscopic perception within a thesis defended recently at the Optics department of IMT Atlantique [146]. Nevertheless, we consider VR headset to be a better option for psychophysical experiments thanks to stimuli isolation from the outside world, larger field of view compared to 3D screens, ability to generate 360 degrees view (with coupled head movements), easier software implementation (through readily available engines like Unity), lower hardware requirements (compared to CAVE). In this chapter, we chose to illustrate the potential of VR headset as an efficient tool for vision research by investigating, through a psychological experiment conducted with a VR headset, how the visual system approaches three-dimensional information.

As presented in Chapter 1, viewing a scene with a VR headset differs greatly from viewing a scene in the real world. Understanding how the visual system processes three-dimensional information is key to insure quality immersive experience and user acceptance.

Imagine a pea covered by a cloth. The viewer can see the hidden pea because of a disruption in the uniformity of the cloth texture. This is possible only due to assumptions of homogeneity and isotropy of the cloth's surface [182], and in fact one could confuse a viewer by painting a bump on the cloth carefully reproducing how light would fall on the homogeneous surface.

To distinguish between a surface and a non-surface, the visual system can utilize information about the relative depth of the input elements. It is well-known that the depth cues (e.g., shading, occlusion, and others) play an important role in visual processing and some studies suggest that objects at the same depth plane seem to be pooled together, even if it deteriorates processing of the individual objects. For instance, Sayim and colleagues [183] studied how vernier acuity was affected by different flankers (a pair of adjacent distractors, see Fig. 4.1). While in most conditions performance declined in presence of flankers, the interference effect was significantly lower when both flankers were closer to or further from

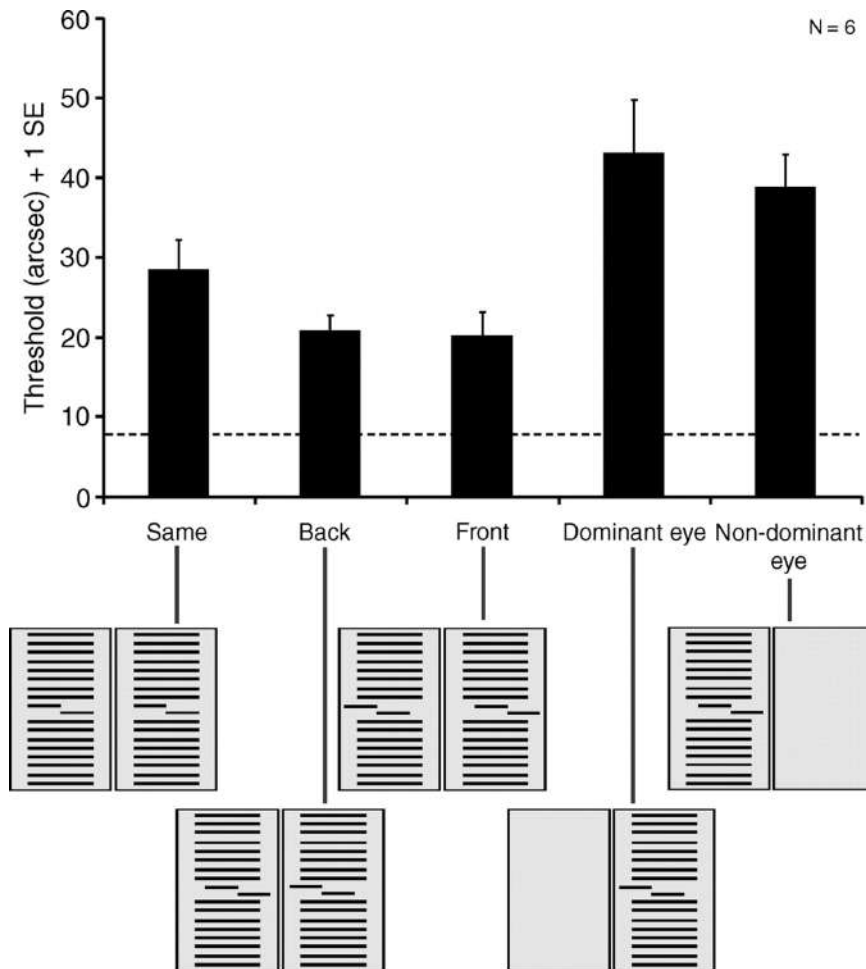


FIGURE 4.1 – *The results reported by Sayim et al. [183]. Vernier thresholds for different stimuli are shown. Stimuli differed in the three-dimensional layout. The illustrations of stimuli are shown at the bottom, they depict left and right eye stimuli separately which produced the depth cue. The results indicate that the Vernier acuity was lower when distractors were located at the same depth as the Vernier stimulus.*

the observer than the target. Andersen and Kramer [184] found a decrease in the effect of incompatible flankers (flankers non-identical to the target interfere with target processing) presented at stereoscopic depth different from the target's depth.

If these studies suggest that stimuli located at the same depth tend to be processed together, other studies indicate that it is not the depth per se but coplanarity that serves as an efficient grouping cue for attention (i.e. objects do not have to be in the same frontoparallel plane but could be embedded in the same slanted surface, see examples from [185] on Fig. 4.2). Huang and colleagues [185] used collinear facilitation paradigm, i.e. Gabor detection threshold reduction in presence of collinear flanking Gabors. They found that the facilitation

was disrupted if flankers and the target did not belong to the same surface, even if they had the same depth. He and Nakayama suggested that “attention in three-dimensional space spreads preferentially and automatically over perceived surfaces“ ([186, p. 4]). In their first experiment, observers looked for an odd-coloured target among distractors in three arrays of different stereoscopic depth. Subjects were significantly faster when the stimuli were coplanar within each array compared to when they were slanted while keeping the same depth within each array. The authors concluded that depth similarity alone was not sufficient to allow rapid search. In the second experiment, stimuli were aligned into three nearly horizontally oriented planes. Subjects, again, were significantly faster when stimuli were coplanar within each horizontal array. This proved that even if stimuli spanned across different stereoscopic depths, the search was still efficient due to appropriate plane attachment. This allowed the authors to conclude that attention is spread along the surfaces without voluntary control.

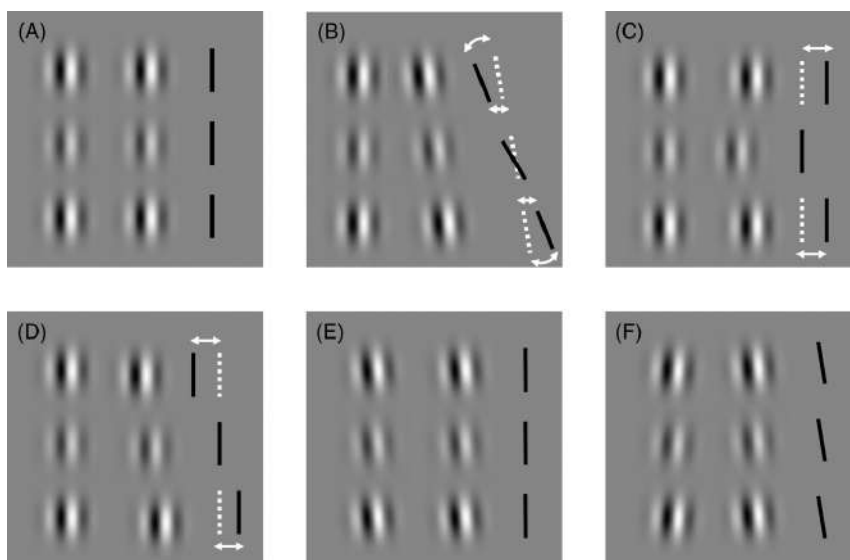


FIGURE 4.2 – **Stimuli from the study by Huang et al. [185].** The figure shows different layouts of stimuli used in the study. They demonstrate different relations between the relative depth and coplanarity in three-dimensional stimuli layouts. On each image, three horizontal pairs of Gabor patches are shown, corresponding to the stimuli presented to the subject; each pair represents left and right eye stimuli. To the right from the patches is shown the depth layout of the stimuli. (A) and (E) depict coplanar stimuli located at the same depth. (B) also depicts coplanar stimuli, but on a slanted surface resulting in different depth of each pair. (F) shows stimuli located at the same depth, but not belonging to the same surface. (C) and (D) show non-coplanar stimuli located at different depths.

As stated previously, the distinction between allocation of attention to surface and to stereoscopic depth is important from a fundamental and practical points of view. It leads to a better understanding of the visual system and the role of pre-attentive scene understanding

in early perception. Practically, this knowledge could help improving visual human-computer interfaces such as in augmented reality or VR (e.g. will depth variation be advantageous at all? How should it be used to split or merge information sources?).

Given the above mentioned evidence for relative depth-dependent involuntary attentional pooling and the benefits given by surface representation to attention distribution, we expect that the information would be pooled more readily across surfaces than across individual objects. This, in turn, might help observers to better estimate the statistical properties of the visual input. Previous studies demonstrated that observers can quickly and effortlessly aggregate information about groups of stimuli ("ensemble statistics" of "visual ensembles"). For instance, in one of the early studies on ensemble statistics, Ariely [187] showed that observers were surprisingly efficient in judging average size of a set of objects despite not being able to identify the objects from the set (see stimuli on Fig. 4.3). The ability to aggregate information about sets of stimuli was demonstrated also for orientation, motion, and even higher-order features (see review in [188]). We expect that when presented with an array of stimuli, observers would be better at drawing ensemble statistics from a set of objects if they could be interpreted as belonging to a single surface rather than a group of separate objects placed at random depths.

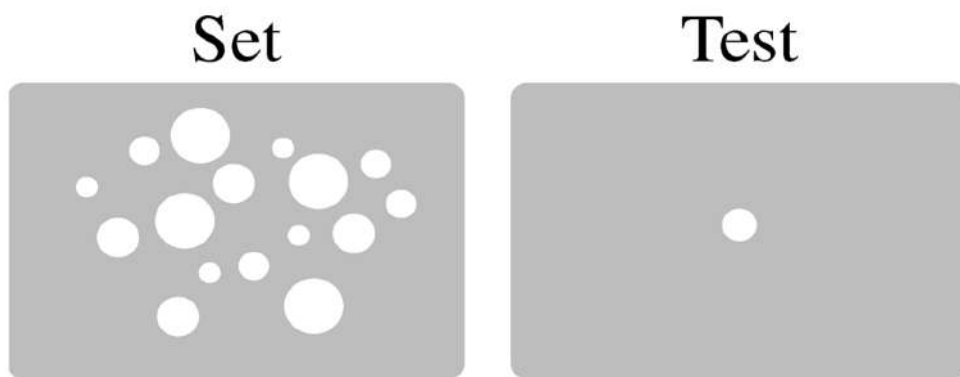


FIGURE 4.3 – *Stimuli in the Ariely's study [187].* On the left is the set of circles with varying sizes that was presented to the subject. Then, subjects were presented with a single circle and subjects judged either if the average size of the previous set was larger or smaller than the test target, or if they saw the target

In order to compare subjects' ability to extract ensemble statistics in objects spread in depth, we used a recently developed behavioral paradigm (coined Feature Distribution Learning) [189–192] to test ensemble perception in three-dimensional stimulus layout. This paradigm involves odd-one-out visual search task where distractors' feature statistics are repeated in a course of several learning trials. Repeated distractors enable observers to learn distractors' feature distribution (its average, variance, and shape (Uniform or Gaussian)).

On a test trial (see Fig. 4.4), the target is then used to “probe” the observer’s expectations about the learnt distractors : if the test target is similar to the previous distractors’ average on the feature range, it will take longer for the subjects to find it than if the test target is far from the learnt average distractors’ feature. By varying the difference between test target and previously learnt distractors’ average, we can probe the whole feature range by measuring subjects’ expectations at every point. In essence, reaction time (RT) to test targets is used to measure how probable distractors are from the observer’s perspective at any given point at the feature range. Thus, the subjects’ representation of distractors can be estimated and reconstructed. Previous studies using this method have shown that observers can encode the parameters of the feature distribution including its shape [189]. This is in contrast to more traditional psychophysical methods that show observers’ sensitivity to the first (mean) and the second (variance) moments of the distribution but not to distribution shape [193]. In our study, the accuracy of this representation provides the estimate of how well attention is allocated and spread across an object group and a texture. Two conditions were designed : the surface (“2D”) condition, in which observers looked for an oddly oriented line, and object (“3D”) condition, in which lines were replaced with cylinders with similar appearance as the lines, and were spread in depth. We expected this to provide a valid estimate of the efficiency of feature pooling from surfaces compared to object sets.

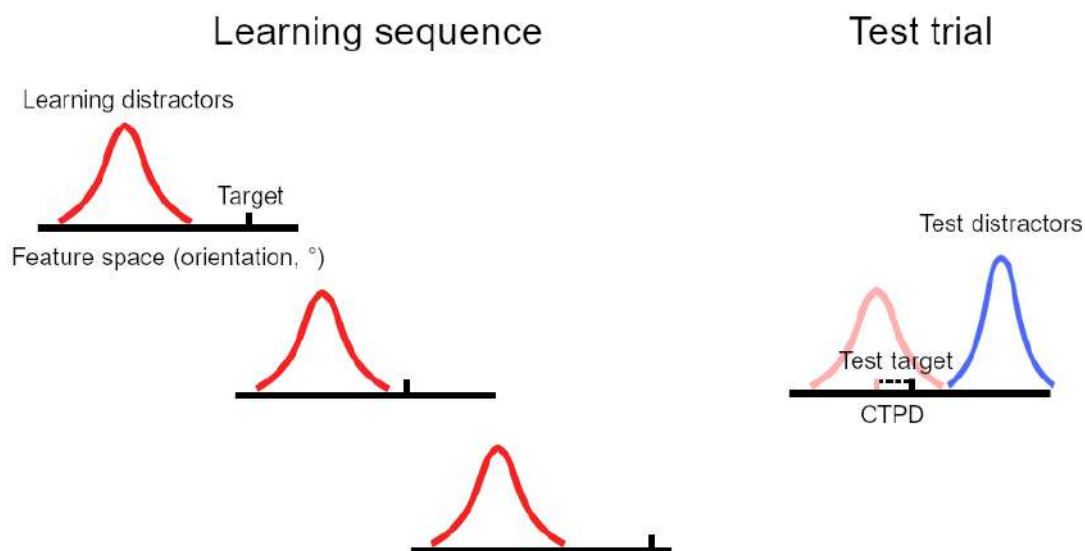


FIGURE 4.4 – **The structure of a block in Feature Distribution Learning procedure.** Each block consists of a learning sequence (4-7 trials) and a test sequence (1 or 2 trials, only first test trial data are included in the analysis). In learning sequence, distractors' range, average, SD and distribution shape is held constant (Gaussian or Uniform with $SD = 15$), and target orientation varies randomly. In the test trial, target orientation is shifted to the current block's value (the difference between current test target and previous distractors' average). Test trial average orientation of distractors (Gaussian with $SD = 10$) is assigned randomly.

4.2 Experiment 1

4.2.1 Methods

Stimuli

In both 2D and 3D conditions, stimuli (see Fig. 4.5) were presented using a VR helmet (Oculus Rift) with Unity software (Unity Technologies) binocularly. Stimulus presentation was administered using a C script in Unity engine.

In each trial, subjects saw 36 white (RGB (255; 255; 255)) lines (cylinders in the 3D condition). The stimuli were presented against four surfaces (“walls”): the horizontal wall below the observer with distance from the observer equal to the observer’s height calculated by Unity software, the vertical wall 2.5 m (distances in virtual units calculated automatically by Unity software) from the observer parallel to the line between the eyes of the observer, and two parallel vertical walls orthogonal to the line between the eyes from the observers on both sides of the matrix 2.5 m away from the observer. The surfaces were covered with

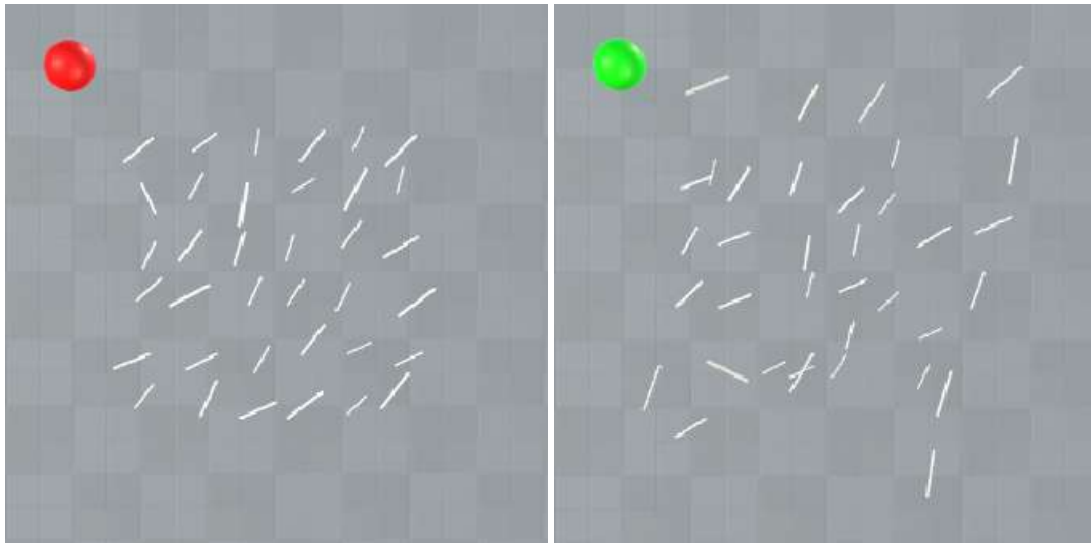


FIGURE 4.5 – **Screen capture of the stimuli in Experiment 1.** The subject looked for the orientation singleton. In 2D condition (left), lines differed in apparent size. The sphere colour was used as feedback for subjects.

checkered-pattern made of dark-grey (RGB (151; 158; 161)) and light-grey squares (RGB (158; 164; 168)), each square with sides of 25 cm. Once the experiment began, the walls' positions were static. The purpose of the walls were to add perspective as additional depth cue for observers and help subjects locate the stimuli in depth. All shadow effects were disabled. The walls were illuminated with two uniform directional lights coming from the top-left and top-right and crossing at the centre of the frontal wall. The lines were additionally illuminated with a point light source to reach uniform lighting of the stimuli.

Stimuli were arranged in a two dimensional 6x6 matrix. Effective distance between the centres of the adjacent cells of the matrix were 9.3 cm (3.2° of v.a. in the 2D condition). Each line was shifted from the centre of its cell randomly by up to 1.4 cm (0.5° of v.a. in the 2D condition) vertically and horizontally. In the 3D condition each cylinder was assigned a distal coordinate in a similar manner to vertical and horizontal coordinates. Distance between the centres of two distally adjacent cells was 18.6 cm, lines were shifted in depth randomly by up to 2.8 cm. In the 2D condition the distance from the observer to the matrix was 165 cm. In the 3D condition, the distance between the observer's initial position and the centre of the stimulus cube was 165 cm. The distance between the centres of the opposite edge cells in 2D matrix was 16°. The distance between the centres of the closest opposite edge cells in 3D matrix was 18.63°.

While in the 2D condition the lines were located at the same stereoscopic plane, in the 3D condition, lines differed in their stereoscopic depth location. However, apparent sizes of

the stimuli in both conditions varied. In 2D condition each line was assigned with a random value representing its virtual depth (in the same fashion, as in 3D condition), and its scale was changed according to its implied depth.

Procedure

Following previous studies with similar design [189], subjects were asked to find a target among distractors - a line (cylinder) whose orientation was the most different from the rest. Once they located the target, they indicated if the target was in the top three rows or in the bottom three rows by pressing one of two corresponding joystick buttons.

Throughout the experiment, in the top-left corner a sphere presented. Its colour was used to give the subjects feedback on their performance. If the response was correct and took less than two seconds, the sphere was painted green. If the response was incorrect or it took more than two seconds, it was coloured red. In addition, if a mistake was made, stimuli disappeared for 1000 ms. If a correct answer was given, the next trial began immediately.

Each block included two sequences of trials : learning sequence and test sequence. Each block had several parameters :

- The learning sequence included from 5 to 7 trials at random. The test sequence included one or two trials.
- The *average orientation of distractors in learning sequence* (DL) was assigned randomly (1-360°) and kept throughout the block learning sequence.
- The shape of the distribution of orientation of distractors was either Gaussian (SD = 15) or uniform (with the range of [DL - 30° ; DL + 30°]). This was the shape that subjects were expected to learn. Distractors in test trials always had the Gaussian distribution (SD = 10).
- The difference between DL and the *target orientation in test trial* (TT), or, in other words, the similarity of the current test target to the previously learned distractors (*difference between current test target and distractors in learning sequence*, CTPD), was a random value within the range of [0° ; 90°] in either rotation direction (clockwise or counterclockwise). Given that we were particularly interested in the differences for targets within the range of previously learned distractors, TT was balanced between blocks so that it would appear equally often in each of the following ranges : ±[0 ; 5°], ±[5° ; 15°], ±[15° ; 25°], ±[25° ; 35°], ±[35° ; 50°], ±[50° ; 70°], ±[70° ; 90°] relative to *average orientation of distractors in learning sequence*.

In the learning sequence, target orientation was calculated by adding to or subtracting from the average distractors' orientation a random value in the range of [60°; 120°]. In the test sequence, while target orientation was assigned according to the current block's CTPD, test trial distractors' average orientation was assigned by adding to or subtracting from the test trial orientation a random value in the range of [60°; 120°].

The difference between the target orientation and average distractors' orientation was assigned randomly for each trial from the range of [60°; 120°]. In test sequence, the difference between the target and the average orientation of distractors was assigned randomly from the range [60°; 120°]. The orientations according to these rules were composed using a custom PsychoPy script.

Before each condition session, all subjects went through approximately 100 trials of training (about 5 minutes). Five times throughout the experiment (evenly distributed), participants were proposed to take a pause to rest. This was done to eliminate possible effects of VR headset use induced discomfort. Participants were encouraged to use the rest opportunity if they needed it.

Analyses

Performance The reaction times were log-transformed for all analyses to reduce skewness of the data and manage outliers [194]. We began by comparing the average accuracy and RT between the conditions to see if depth variation influenced subjects' performances.

Repetition effect We proceeded by checking if observers had benefited in learning information about distractors from repeated distractor distribution during learning sequences by analysing the repetition effects. This was done using linear mixed-effects regression with Helmert contrasts (comparing each trial mean with the mean of the subsequent trials within the sequence) separately for each condition (mixed-effects models were fitted using 'lme4' package for R [195], p -values were calculated using 'lmerTest' package [196]). Reaction time was used as the dependent variable, the number of the trial within a sequence was used as the fixed effect, and participants' intercepts were introduced as the random effect.

Role-reversal effect After the repetition effect, we investigated the effect of disruption of this repetition, referred to as role-reversal [197], which occurs when after a sequence of trials with repeated distractors (learning sequence in our study) whose feature distribution occupied a certain range within the feature space (in our case, the feature space is 360° which can be assigned to a line), follows a trial where the target falls within the feature range

previously occupied by distractors (test trial in our study). Because the test target falls on the range of the feature space that the subject learnt to suppress, the subject's performance suffers. This suppression is higher when the target is within the previous distractors' range compared to the test target which is outside the previous distractors' range.

For instance, if subjects has learnt that in the course of n trials the distractors that should be suppressed in order to find the target fall within a range between 60 and 90 degrees, if in trial $n + 1$ the subject would be prone to use this suppression to speed up the search. However, if in trial $n + 1$ the target falls within the range of the previous distractors (60-90 degrees), the subject would initially suppress it.

If distractors' orientation distribution is not uniform, this unequal probability can be reflected in the subject's representation of this distractors' distribution. Say, if there are more distractors closer to the distractors' average, this would be reflected in different level of suppression of the test target depending on its relative position to the previous distractors' average. I.e., the level of suppression would depend on the previous distractors' probability density function [189]. The level of suppression is measured using test trial RT. In our case, RT is taken as a function of the difference between the current test trial target orientation and the previous distractors' average orientation (CTPD) [198]. Only correct first trials within test sequence preceded by a correct learning sequence trial.

Returning to the example above, if the learnt distractors' orientation was not uniformly distributed along the range (60-90 degrees), but instead average values prevailed significantly (around 75 degrees), subjects would spend more time looking for the test target around 75 degrees because it would take more time for to overcome the suppression of the average of the previous distractors.

If the learnt distractors' distribution shape is uniform, the RT would be higher (the suppressed level) within the previous distractors' range and would be reduced outside the previous distractors' range (the non-suppressed level). If the learnt distractors' distribution shape is Gaussian, the RT would be the highest if the test trial target's orientation is equal to the previous distractors' average orientation and would gradually decrease as CTPD increases.

We assessed the accuracy of the distractors' distribution representation by comparing the RT as function of CTPD to three predefined functions based on the previous studies [191; 198; 199] :

1. Null model represented lack of dependency.
2. Uniform model with linear decrease was a two-part function, whose value was constant within the distribution range, but fell linearly outside the range.

3. Gaussian model represents gradual Gaussian-like decrease.

Each model has parameters with predefined ranges [199]. By manipulating these parameters, each model is fitted to RT as function of CTPD following maximum likelihood estimation algorithm ('bblme' package [200] for R). As the result of this procedure, we obtain the parameters for each model (the maximum likelihood estimates) with which the given model's posterior probability is the highest (i.e., the probability of the model with maximum likelihood estimates as parameters given the empirical RT) and the value of Bayes Information Criterion (BIC). BIC serves as the estimate of likelihood (goodness of fit) of the most likely version of each model. The model which receives the lowest BIC is the best fit [201].

Then, the difference between the lowest BIC and the second lowest BIC (Δ BIC) provides an approximation to Bayes Factor which can be used to assess the statistical significance of the evidence in favour of the model with the lowest BIC [202] :

- If Δ BIC < 2 - insufficient evidence;
- If $2 > \Delta$ BIC < 6 - positive evidence;
- If $6 > \Delta$ BIC < 10 - strong evidence;
- If Δ BIC > 10 - very strong evidence.

Participants

15 participants (mean age 25.3 years, SD = 3.65, 2 females) were recruited among students in local engineering schools. Subjects were included into the experiment if they did not have any medical record of serious visual impairments. Subjects with corrected myopia or hyperopia, astigmatism or anisometropia are allowed to participate. The study was carried out in accordance with the tenets of the Declaration of Helsinki. Written informed consent was obtained from all participants.

4.2.2 Results

On average subjects were more accurate in 2D condition ($F(1,15) = 14.04, p = .002$). No statistically significant differences in RT was found ($F(1,15) = .07, p = .8$).

The analysis of the effect of the trial number within learning sequence (see Fig. 4.6) showed that in 3D condition RT decreased after the first trial ($t = 3.773, p < .001$). RT also increased in trial 5 compared to both the following trials ($t = 1.98, p < .047$) and the preceding trials ($t = -2.03, p < .021$) which means a jump in RT in trial 5. No significant effect of trial number in learning sequence in 2D condition was found.

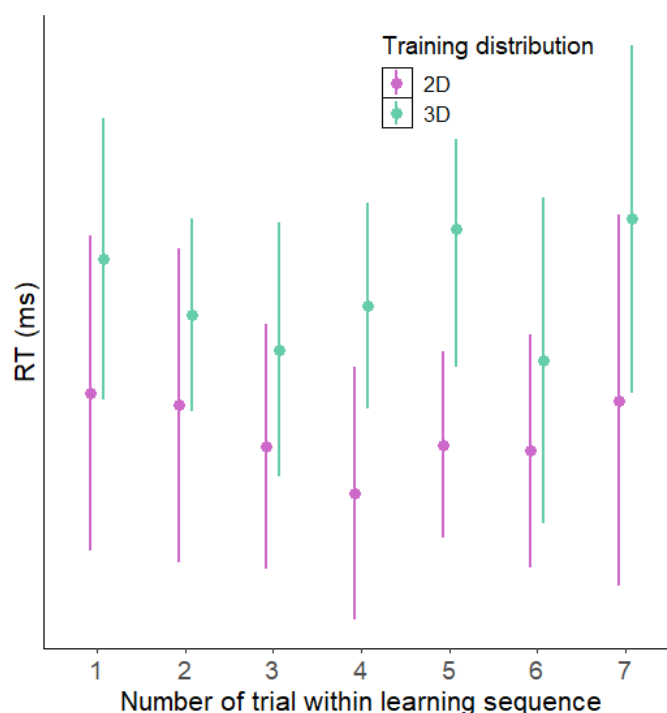


FIGURE 4.6 – *The effect of the learning sequence trial number on reaction time in Experiment 1. Reaction time is scaled on the ordinate axis, the number of the trial in the learning sequence is on the abscissa axis. The colour marks the condition. The error bars represent 95% CI. The analysis showed significant decrease in reaction time after the first trial and after fifth trial in 3D condition.*

Our predictions did not match the model fitting results (Fig. 4.7). In 2D condition, marginal evidence was found ($\Delta\text{BIC} = 1.98$) for our uniform model with linear decrease as the closest to the shape of empirical RT as function of CTPD in test trials after distractors with Gaussian distribution of orientation, which contradicts with our expectations. In 3D condition, learning distractors with Gaussian-like distribution of orientation did not receive notable evidence ($\Delta\text{BIC} = .34$). Distractors with uniform orientations produced a function of RT which did not depend on CTPD in both 2D ($\Delta\text{BIC} = 3.49$) and 3D condition ($\Delta\text{BIC} = 4.03$) (see Tab.4.1).

4.2.3 Discussion

In the present study, we used Feature Distribution Learning procedure [191; 198; 199; 203] in order to measure the accuracy of the ensemble representation of a group of stimuli. We used this measure to compare the accuracy of the representation of a group of stimuli belonging to the same surface to the group of stimuli varying in depth, thus holding the impression of separate objects. Following the results established in this paradigm, we expected that 2D

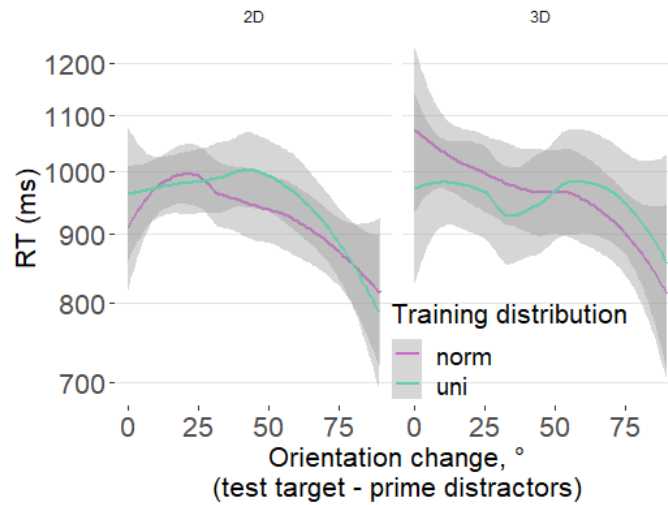


FIGURE 4.7 – **Reaction time as function of difference between test trial target and previous learning sequence average distractors' orientation in Experiment 1.** Reaction time is scaled on the ordinate axis, difference between the test trial target and learning sequence distractors' average orientation is on the abscissa axis. The colour marks the condition. The grey area represents 95% CI. 2D condition results are on the left, 3D results are on the right,

condition would replicate the pattern of results reported in previous studies where the stimuli were presented on a regular desktop screen.

According to this pattern, we predicted that in test trials, following learning sequence with repeated parameters of distractors' orientation, RT as function of CTPD would reflect the probability density function of distractors' orientations. This implies that :

- after distractors with Gaussian-like distribution of orientation, RT would be the highest if the TT is the closest to the average distractors' orientation, and roll off gradually as CTPD increases, until it reaches the edge of the distractors' orientation range (30°).

Distribution shape	Condition	Best fit	Δ BIC
Gaussian	2D	Insignificant	1.98
Uniform	2D	Null model	3.49
Gaussian	3D	Insignificant	.34
Uniform	3D	Null model	4.03

TABLE 4.1 – **The results of model fitting in experiment 1.** The first column lists the distractors distribution shape, the second column states the condition. The third column represents the model which was found to be the best fit to reaction time as function of the difference between learning sequence distractors and test trial target. The fourth column shows the approximation of Bayes factor when the best fit and the second best fit models are compared.

- after distractors with uniformly distributed orientation, RT would plateau near the TT at average distractors' orientation, and roll off gradually as CTPD reaches the edge of the distractors' orientation range (30°).

Because our results contradict to these predictions, we conclude that our subjects did not manage to learn the distractors' distribution shape. What is particularly important, these predictions were not fulfilled even in 2D condition, purpose of which was to replicate the previously reported results. Additionally, our results also did not show gradual decrease in RT within learning sequences, while it was pronounced in studies using Feature Distribution Learning paradigm, as well as in other studies studying repetition effects [197].

Thus, it was decided to conduct another experiment with 2D condition following more closely the previous studies administered using a desktop screen. For this reason, several changes to the experimental design were made. The purpose of these changes was to make a more vivid impression of the plain surface in 2D condition.

4.3 Experiment 2

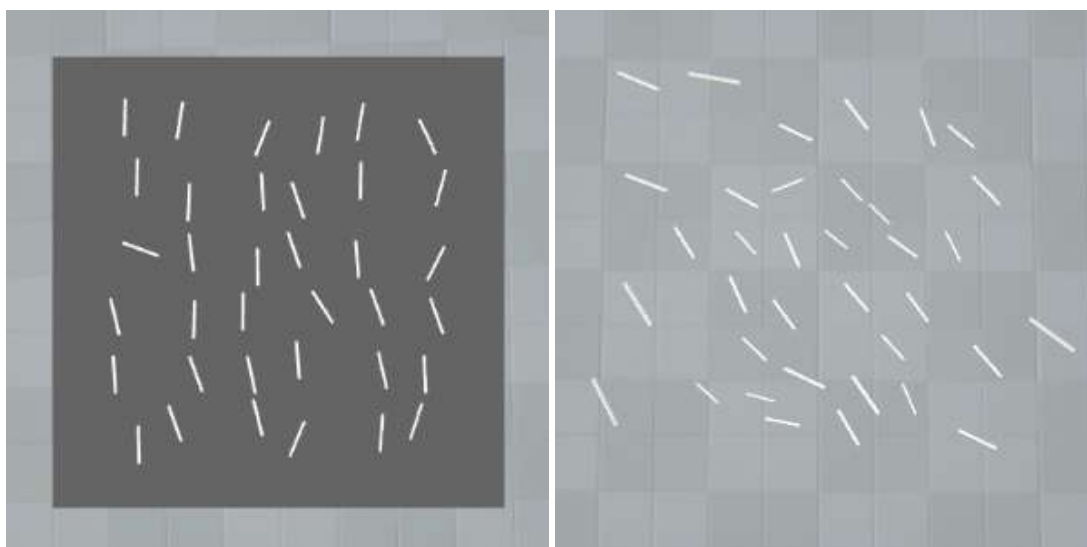


FIGURE 4.8 – **Screen capture of the stimuli in Experiment 2.** The subject looked for the orientation singleton. The 2D (left) differed from 3D condition (right) in four aspects : the grey background was added, lines did not vary in apparent size or apparent depth, the position of the lines was anchored to the headset position and rotation

4.3.1 Methods

Following changes to the procedure of Experiment 1 were introduced :

1. The number of blocks for each condition was twice higher (312). Subjects passed the test in two experimental sessions on two separate days. The number of breaks was doubled, too.
2. In the 2D condition, line sizes did not vary (see Fig. 4.8).
3. While in Experiment 1 lines were presented in one invisible depth plane, in Experiment 2 they were presented on a grey rectangle located at the same depth.
4. While in Experiment 1 in 2D condition the lines were presented at a certain position in space, in Experiment 2 the position of the matrix was anchored to the position and rotation of the headset : the distance and the orientation of the plane of the matrix was constant relative to the observer's head thus eliminating the depth cue of binocular parallax.
5. Throughout the experiment, in the top-left corner the ongoing total score was presented (instead of the sphere). Score was summed after each trial using the following formula :

$$TS = 10 + (1 - RT) * 10$$

where TS is a current trial score and rt) is reaction time in seconds. If the response was correct and the trial score is positive, the score was painted green. If the response was incorrect, the absolute value of the trial score increased by 10 was subtracted from the total score. If the trial score was not positive, it was coloured red. In addition, if a mistake was made, stimuli disappeared for 1000 ms and a word "error" in capital letters in red appeared. If a correct answer was given, the next trial began immediately. The score rested unchanged until the next response was given. During breaks, the total score was shown.

6. Because the duration of the test increased considerably, the subjects were paid for their participation.

Participants

10 participants were recruited among students in local engineering schools and paid 30 € for their participation. Subjects were included into the experiment if they did not have any medical record of serious visual impairments. Subjects with corrected myopia or hyperopia,

astigmatism or anisometropia are allowed to participate. The study was carried out in accordance with the tenets of the Declaration of Helsinki. Written informed consent was obtained from all participants.

4.3.2 Results

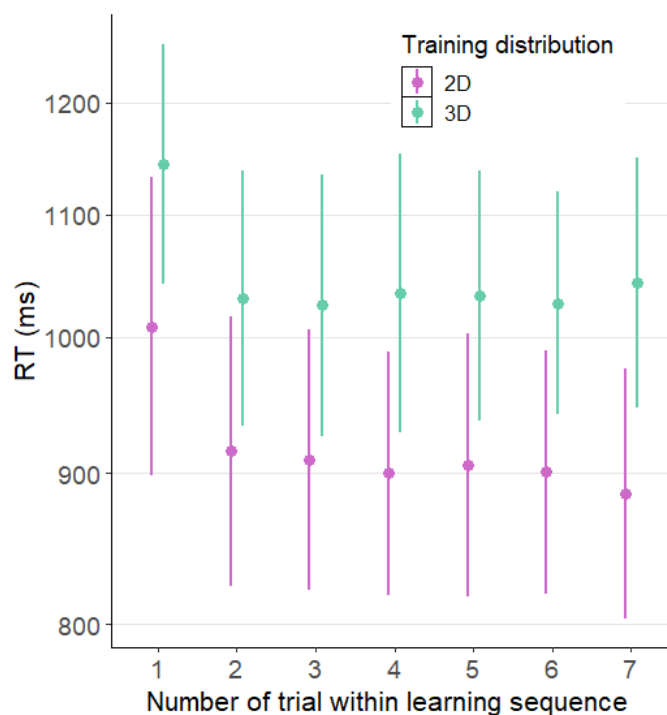


FIGURE 4.9 – *The effect of the learning sequence trial number on reaction time in Experiment 2.* Reaction time is scaled on the ordinate axis, the number of the trial in the learning sequence is on the abscissa axis. The colour marks the condition. The error bars represent 95% CI. The analysis showed significant decrease in reaction time after the first trial.

The data were analyzed in the manner analogous to Experiment 1. Repeated measures ANOVA did not show statistically significant differences between the conditions in RT ($F(1,9) = 2.78, p = .13$). However, subjects were more accurate in 2D condition ($F(1,9) = 10.45, p = .01$).

Helmert contrasts in training sequences showed that in both conditions RT decreased after the first trial (2D : $t = 11.98, p < .001$, 3D : $t = 10.78, p < .001$) (see Fig. 4.9).

Model comparison, again, did not show the expected results (Fig. 4.10). Δ BIC reached value greater than 2 only in 2D condition for Gaussian distractors (Δ BIC = 3.61) and in 3D condition for uniform distractors (Δ BIC = 2.11), and, moreover, in all four cases the uniform



FIGURE 4.10 – *Reaction time as function of difference between test trial target and previous learning sequence average distractors' orientation in Experiment 2.* Reaction time is scaled on the ordinate axis, difference between the test trial target and learning sequence distractors' average orientation is on the abscissa axis. The colour marks the condition. The grey area represents 95% CI. 2D condition results are on the left, 3D results are on the right,

model with linear decrease was favoured, which contradicts with our predictions for Gaussian distribution in 2D condition. Therefore, we must conclude that the subjects, again, failed to learn the distribution shapes in both conditions.

4.4 General discussion

There were two comparisons planned for the present study aiming at finding the differences in processing a similar input in two and three dimensional layouts. The first focused on the comparison of behavioral data (RT and accuracy), and the second involved the comparison of accuracy and complexity of the ensemble representation. Our motivation to compare two- and three-dimensional stimuli came from the previous studies which pointed at possible mechanisms underlying the way the visual system processes textures and object ensembles.

In our study, the subjects viewed groups of stimuli (lines) and searched for an orientation singleton in two-dimensional and three-dimensional layouts. Processing the 3D-layout of the scene is thought to precede more complex processes, such as visual search, and, consequently, influence them [204–206]. The visual system has been shown to use the advantages of processing coplanar stimuli, which manifests in faster joint processing of coplanar objects

compared to groups of objects extended across depth [185; 207] and easier suppression of non-coplanar distractors [208; 209]. But also performance seems to suffer when distractors are located at the same depth as the target [184; 210]. This allows to infer involuntary feature pooling based on depth, which in turn pushes forward the proposition of existence of a special mechanism dedicated to processing of surfaces. In fact surfaces were given a special status in visual processing, because belonging to the same surface was shown to impose greater influence than same distal position [185; 186; 205; 206] (but [211; 212]).

This led us to make two predictions in regard to the difference between 2D and 3D conditions. First, we predicted higher accuracy and lower RT based on the hypothesis of easier processing of co-planar stimuli. Surprisingly, despite frequently voiced opinion of our subjects concerning greater difficulty of the task in 3D condition, we found that only accuracy differed in both experiments.

Second, we expected that distractor repetition effects would be more pronounced in 2D condition allowing for a higher precision representation of distractors. We used Feature Distribution Learning procedure for measuring the precision of the statistical ensemble representation [199]. The failure to replicate even basic effect of decreasing RT after distractor repetition [197] in Experiment 1 suggested that the 2D as the replication condition should follow more closely the original test procedure. Despite better learning, model comparison failed to replicate the original findings shown in Feature Distribution Learning paradigm [191].

CONCLUSION

Recent technological advances, in particular in terms of displays and sensors, have allowed VR headsets to enter the consumer market (2016) and to find applications in an increasing number of fields (entertainment, education, marketing, etc.). The fundamental design of these helmets is, however, still very close to the stereoscope developed by Wheatstone (1838) for his work on binocular vision. As a result, these new headsets represent both a potential risk for the human visual system but also a powerful tool for studying it in a controlled environment. The present thesis addressed this duality.

The first chapter of the thesis describes virtual reality and human vision. We describe the design of VR headset and how it interacts with the visual system. We also provide the outline of the anatomy of the visual system.

The second chapter is divided into three studies focusing on the potential negative impacts of VR headsets on the subject. In the first study, we assessed if VR headsets have a similar impact on blinking and the lipid layer thickness than conventional desktop monitors. Blinking actually plays an important role on eyes' health and reduced blink rate has been reported with computer use. We show that the impact of VR headset use on blinking activity is comparable to that of regular desktop screen. However, future studies could test this effect with more demanding virtual experiences, which are far more popular among VR users.

In the second study, we focus on perceptual aftereffects of VR use. In particular, we investigate if the spatial spread of attention is altered after adaptation to restricted field of view of a VR headset in perceptually soliciting environment. The results of this experiment suggest that VR use can lead to deteriorated processing of the central visual field. This result, however, demands confirmation in a balanced experimental design. Testing the effect of different VE enabling different attentional strategies could be of interest in this context.

In the third study, we investigated factors contributing to the symptoms of VR induced discomfort. Although the issues of VR induced cybersickness or eyestrain are well known, as well as the associated risks factors, most studies have focused on reducing it or assessing this discomfort rather than predicting it. Since the negative experience of few users can have a strong impact on the product or an event's publicity, we tried to develop a questionnaire to help a user to rapidly and accurately self-assess personal risks of experiencing discomfort before using VR. This study suggests that a prospect tool with such purpose could benefit from a combination of subjective and objective measures. Also, based on our results, we recommend that experiments aiming at assessing the cybersickness symptoms severity involve more provocative VE in order to obtain data better fitting the statistical analyses' requirements.

In order to provide us with a tool that would offer us more control on the display parame-

ters and possibly simulate new approaches (e.g., multifocal displays) we built a motorized haploscope. The third chapter presents its construction (hardware + software) and its use in the fifth study investigating aniso-accommodation. The results of this study show evidence against functional, naturally occurring aniso-AR. A prospect study could involve the similar test with different stimuli which could present a better accommodation stimulus.

The fourth chapter investigates one of the possibilities brought by VR technology in the study of vision. The importance of 3D display in VR and the potential of VR headset to study 3D vision led us to investigate the spread of spatial attention in depth. We tried to answer the question if it is easier for humans to allocate attention to a group of objects belonging to the same surface rather than to stimuli spread in depth, and how it influences the result of processing groups of objects and building their statistical representation (i.e., ensemble statistics). Because we failed to replicate the previously reported results with the procedure used in this experiment, we conclude that some particular traits of VR that we ignored in this study may need to be taken into account (e.g., accommodation-vergence conflict, image resolution or setup appearance).

The present thesis investigated the dual aspect of the link between VR technology and vision science. On one hand, we realized three studies which used diverse methods to study different aspects of the impact of VR on the visual system. On the other hand, we used VR as an instrument for stimuli presentation which offers wider range of three-dimensional stimuli. We also constructed a custom motorized haploscope as a tool allowing for objective measurement of oculomotor response and controlled stimuli presentation. This haploscope can both serve as a model of stereoscopic displays to study their impact on visual system and as a potent experimental tool on its own for investigating binocular vision.

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Titre : Vision humaine et réalité virtuelle : comment réalité virtuelle peut impacter le système visuel et aider l'étudier

Mot clés : vision, réalité virtuelle, perception

Résumé : Les rapides progrès technologiques ces 10 dernières années ont permis un essor de la réalité virtuelle (RV) auprès du grand public. Cependant, le design des casques de RV modernes reste toutefois très similaire au stéréoscope original développé par Wheatstone (1838) pour ses travaux sur la vision binoculaire. En conséquence, ces nouveaux casques représentent à la fois un risque potentiel pour le système visuel mais aussi un outil puissant pour l'étudier dans un environnement contrôlé. La présente thèse aborde cette dualité.

Le premier chapitre présente l'architecture d'un casque de RV et son lien avec le système visuel.

Le deuxième chapitre rapporte trois études qui examinent les risques associés à l'utilisation du casque VR sur la santé oculaire, l'attention visuelle et l'inconfort (cinétose et fatigue visuelle).

Le troisième chapitre présente la construction d'un haploscope motorisé afin de nous fournir un outil offrant plus de contrôle sur les paramètres d'affichage et son utilisation dans une 4ème étude sur l'aniso-accommodation.

Le quatrième chapitre porte sur le potentiel offert par la RV pour l'expérimentation psychophysique via une étude sur comment le système visuel regroupe les informations dans une scène 3D.

Title: Human vision and virtual reality: How virtual reality can impact the visual system and help studying it

Keywords: vision, virtual reality, perception

Abstract: Recent years marked significant technological advances in VR technology. However, the design of modern VR headsets still bears the traits of the original stereoscope constructed by Wheatstone (1838). This thesis addresses the issues of risks and vision research opportunities that are brought by this heritage.

In the first chapter of the thesis, we introduce the VR headset design and how it interacts with the visual system. The second chapter reports three studies that investigate the risks associated with VR headset use that originate

in its design: ocular health, cognitive aftereffects and cybersickness.

In the third chapter, we present a motorized haploscope which in some aspects surpasses VR headset as a vision research instrument. We also report the results of the study of aniso-accommodation response conducted using the haploscope.

The fourth chapter demonstrates the capabilities of VR in psychophysical experiments. In this experiment, we used VR headset to investigate how the visual system pools information in a three-dimensional scene.