Visual disorders due to exposure to 3D displays or to immersion into Virtual Reality: A literature review

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1. INTRODUCTION

3-Dimensional (3D) technologies have recently been subjected to a rapid increase in popularity, whether it concerns 3D television and theaters, gaming products or Virtual Reality (VR). Virtual Reality is a simulation or a projection of a 3D environment in which sensory experiences are created artificially by an interactive software [1] [2]. Virtual Reality slightly differs from traditional 3D displays in that it creates a full stereoscopic experience instead of a brief immersion in the 3D world, as this immersion ends when one would for instance see the edges of the screen in a movie theater. VR headsets allow a full immersion in the 3D space.

However, with more and more users, side effects are being increasingly reported, leading to safety and health concerns [3] [4]. In order to assure the growth of their market, 3D technology companies have to guarantee high image quality and viewing comfort, which pressures them to research on the causes of visual discomfort ("visual discomfort" refers to the entire panel of health related symptoms caused by immersion in a 3D environment).

Side effects

Since first developed in the 30s [5], stereoscopic displays have been the subject of numerous social and medical studies [3] [4] [6] [7]. Paired with user complaints, they lead to the conclusion that 3D technologies can pose a risk the user's health. Although the recent advances of digital technologies have allowed the improvement of many issues regarding the generation and transmission of stereoscopic content [3], viewer discomfort is still a problem. The reported side effects include an increased heart rate, tired eyes, headaches, nausea, disorientation and dizziness.

Based on the increasing number of complaints [3], 3D-technology companies have released warnings concerning which users are most at risk of suffering from the aforementioned side effects. For instance, after releasing the Gear VR Innovator, a virtual reality headset, Samsung emitted a warning that pregnant women, children, elders and individuals suffering from motion sickness could be at risk of confusion, nausea, convulsions, altered vision and dizziness [8]. Young children are prone to experiencing side effects from immersion in VR, or any other 3D technologies, because of their small IPD (interpupillary distance) [9]. Most adult people's eyes are separated by a distance of 2.5 inches, which is not the case for children. 3D films being conceived

with an adult IDP in mind, children will not be able to vision the movie properly. Furthermore, the intense eye muscle solicitation involved in viewing 3D films will lead to fatigue in children, as their eye muscles are not yet fully developed (this is further explained in the section *Accommodation and vergence*). Children with vision problems (5-10% of the population) should be even more cautious in stereoscopic viewing, as this can increase the degree of the disorder [9]. Indeed, 3D images cause the development of nearwork-induced transient myopia (NITM), a short-term myopia, which has an effect on the development and the progression of a permanent myopia [10]. Concerning pregnant women, experiencing 3D/VR side effects such as dizziness, which is characterized by not enough blood flowing to the brain, may harm them and eventually their baby.

As an example of study, 953 subjects were asked to answer a series of questions during, right after and two hours after watching a 3D commercial [3]. The study was aiming to quantify the occurrence of the reported symptoms of visual discomfort. The results show that two thirds of the individuals experienced side effects during the movie, a third reported them after the movie and a quarter, two hours after. Two individuals experienced strong signs of visually induced motion sickness and four of the participants found that the severity of the symptoms increased after watching the movie. Although in this study the side effects did not pose a serious health risk and disappeared quickly, the study emphasizes that further research needs to be done on the effects of 3D technologies regarding long-term use. Furthermore, it is also necessary to understand the reasons why some people recover slower than others after being subjected to 3D movies.

2. HUMAN PERCEPTION OF DEPTH

Human eyes function according to binocular depth perception. Indeed, since the two eyes are separated by a certain distance, they do not send the exact same image to the brain. The brain analyzes these two slightly different images and extracts the relative depth information in order to create a stereoscopic view. The perception of depth based on image differences from the two eyes is referred to as binocular depth perception, or stereopsis [9].

Individual differences in stereoscopic vision

Stereoscopic depth perception varies from one individual to another because their visual systems slightly differ. For instance, as mentioned previously, IDP is a characteristic that not only differs between age groups, but also amongst individuals from the same group. On average, adults have an IPD ranging between 50mm and 70 mm. However, by including children and extremes, this range is broadened to 40mm-80mm. A small IPD leads to an increased stereoscopic depth perception. This is why children feel the consequences of too much stereoscopic screen disparity more strongly than adults do [9]. Researchers thus prefer to advise children against the use of 3D technologies because the severity of their impact on the visual system has not yet been determined. Lastly, with age, visual abilities (including focusing and muscle contraction) decrease, following progressive changes in the eye structures, ex.: hardening of the eye lens (presbyopia), increased

risk of developing glaucoma (damage to optical nerves), reduced pupil size, vitreous detachment or decreased color vision (color-perception cells on the retina become less sensitive) [11]. Therefore, children have a very flexible vision system whereas accommodative abilities are generally weak beyond the age of 55.

Accommodation and vergence

When subjected to a visual stimulus, both eyes will move at the same time in slightly different directions, in order to create and maintain single binocular vision. This is called vergence and it occurs when focusing on an object. Human vision is therefore based on retinal (binocular) disparities, which refers to two eyes seeing the same scene from two slightly different angles [12]. The small difference between the two images can be quantified as zero or non-zero (expressed in terms of visual angle) with respect to the images (foveas), on both retinas, of a reference (fixation) point in space, in front of the eyes (see Figure 1, a) [13]. The locus of points in space generating zero retinal disparity is called a horopter. Theoretically, this means that, for all those points, the angle between the lines of sight of the two eyes is constant, meaning that they lay on a circle passing by the fixation point and the nodal point of each eye (see Figure 1, b). Since the horopter is determined using the two pupils, the IPD can make thus make the horopter size vary from one individual to the other. Furthermore, the real (empirical) horopter differs from a circle, since the eyes are not perfectly spherical (see Figure 1, b). This means that even two people with the same IPD can have a slightly different horopter. This leads to additional challenges in the perception of 3D videos.

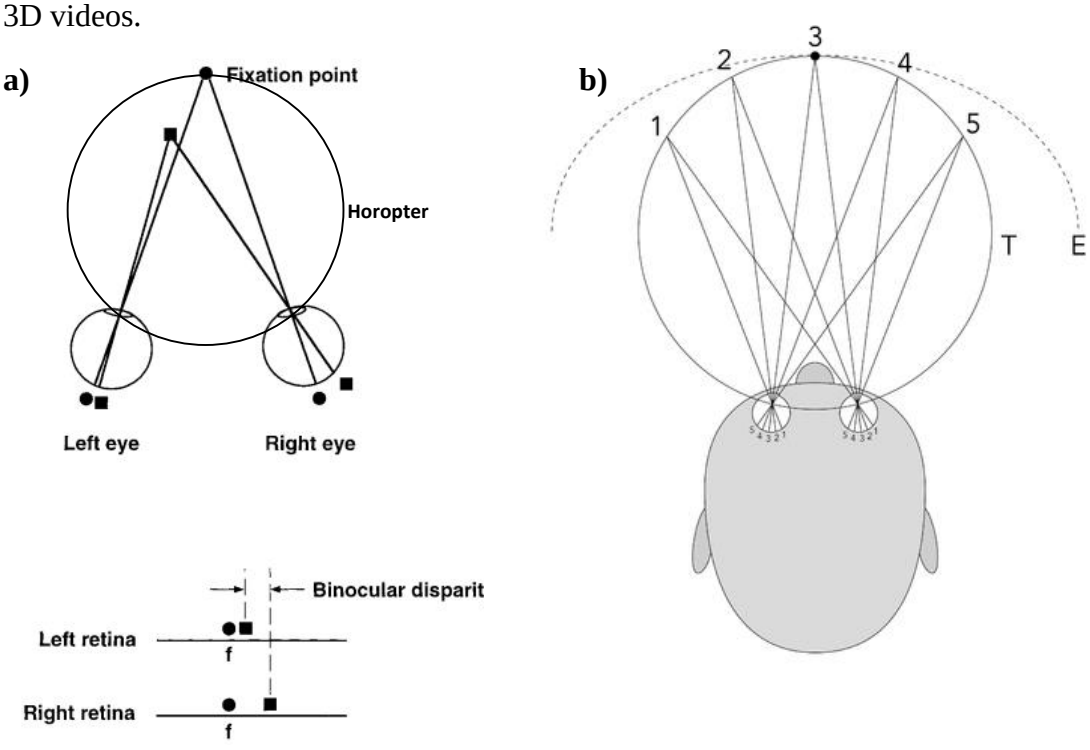

Figure 1: a) *Retinal disparity happens on out-of-horopter points; b) Constant viewing angle on each point on the horopter. The empirical horopter is labelled as "E"* **[13] [14]**.

Furthermore, the eyes are able to correct blur by changing the curvature of their lens. This ability of the eyes to change their focus between near and distant objects is called accommodation [15]. Vergence and accommodation are neurologically coupled [12] [15]. In natural viewing, vergence and focal distance are almost always identical which makes vergence-accommodation coupling advantageous (Figure 2, A). However, in artificial stereoscopic viewing, the focal distance is fixed at the display distance but the eyes have to verge wherever the object appears in space (Figure 2, B). Figure 2, C and D show the corresponding perceived focusing effects. This disrupts the natural correlation between these two processes (often referred as asthenopia), which causes: 1) perceptual distortions; stereoscopically created structures will be distorted compared to the real scenes that the displays illustrate, 2) visual discomfort and fatigue as the viewer attempts to adjust the vergence and accommodation, and 3) difficulty in fusing and focusing the object [12]. Practically, in artificial 3D, if the accommodation is accurate, the object will be clear but one might see two objects, and if vergence is accurate, there will be a single blurry image [12]. An increased solicitation of the extraocular muscles is needed in order to try to match the vergence and the accommodation of the eyes. For instance, control conflict may appear if the correct accommodation might require those muscles to contract, whereas a proper vergence might need them to relax.

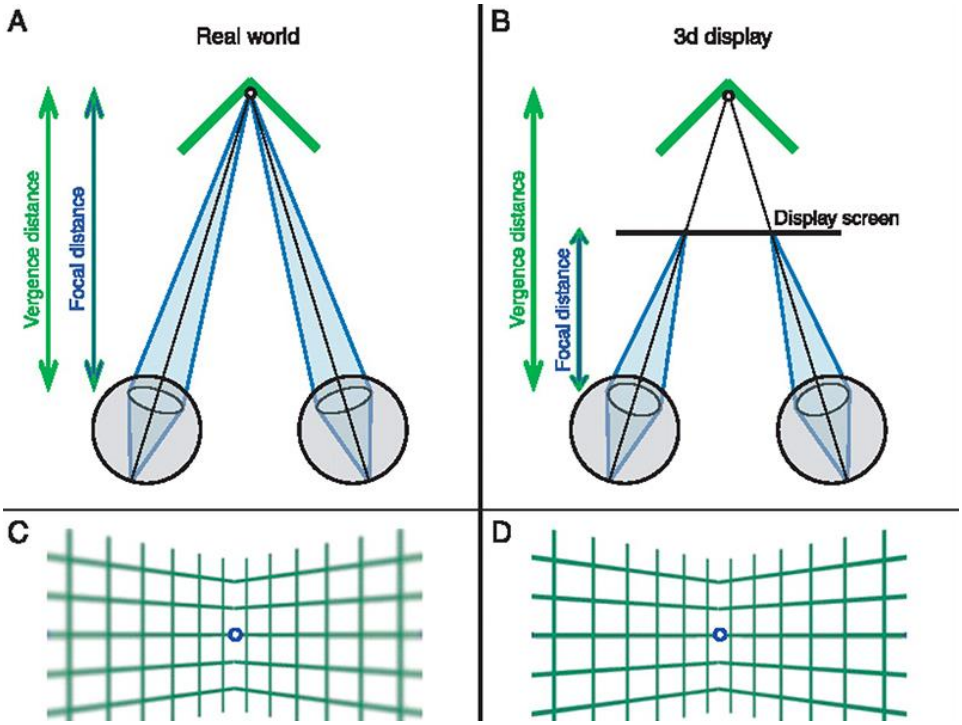

Figure 2: Vergence and accommodation in real-world viewing (A), on 3-D displays (B), and corresponding focusing effects (C and D) **[16]**.

Visual fatigue and visual discomfort

There is a difference between visual fatigue and visual discomfort, although the literature often uses these two terms as synonyms. They both refer to the decrease in performance of the vision system. Visual fatigue refers to the objective measurements of such decrease in performance, whereas visual discomfort measures it subjectively. Analysis of visual discomfort can thus give an indication of the expected measurements for visual fatigue. Subjective measures, which have been proposed by many researchers, include questionnaire and psychological scaling [4]. Objective measures, which have been studied in only few works [9], include optometric measurement and brain activity measurements, such as EEG, MEG and fMRI [4].

Brain areas involved in depth perception

The depth perceiving vision is involved in the viewing of objects in motion, as it is an assessment of their trajectories through space. Neurons located in the occipital lobe are involved with depth perception, as they are able to decode differences between the images perceived by the left eye and the right eye in order to create a stereoscopic image [7]. However, the process of visualizing a scene also involves the temporal region for memory processes and the frontal lobe (with the perirhinal cortex) for object recognition. Brain research using fMRI (neuroimaging procedure that detects changes in blood flow) in humans has shown that neurons from brain areas V3A, V7, V4 (see Figure 3, A, C) and the caudal parietal disparity region are involved in stereoscopic processing [4]. An increased cortical activity is also recorded in the MT+ area when viewing 3D images (see Figure 3, B) [4].

The MT (also called V5) area (see Figure 3, C) has a high concentration of neurons responsive to motion stimulus, and is much less responsive to other types of visual stimulus, such as shape or color. This can be explained by the high incidence of directionally selective neurons in the area relative to other visual areas [17]. Furthermore, some MT neurons, called type II neurons, are able to extract information coming both from the orientation of an object and the direction of its movement, thus forming a cell class responsible for higher level motion processing [18]. This supports the hypothesis that each visual area has a distinctive role in analysis of visual stimuli [7].

fMRI experiments were used to quantify and establish how visual fatigue and cortical activity are related [4]. Since visual fatigue is possibly caused by excessive binocular disparities, such studies objectively measure the brain activity. For example, an apparatus in a 3 Tesla MRI system [4] was used to measure the response to various degrees of binocular disparity from visual stimuli delivered. For image processing and statistical analysis, the data was analyzed using a statistical parametric mapping software (SPM) implemented in MATLAB. The results confirmed the strong cortical activity in the V3A area. Furthermore, the study allowed to determine that excessive binocular disparity affects the frontal eye field (FEF), region responsible of controlling eye movements (see Figure 3, A). An increased cortical activation was also observed in the FEF (and V3A) region when the volunteers were subjected to two different binocular disparities out of the comfortable viewing zone. Excessive disparities thus lead to an abnormal activation of the

human oculomotor system, which explains why visual fatigue is one of the most reported side effect of 3D immersions.

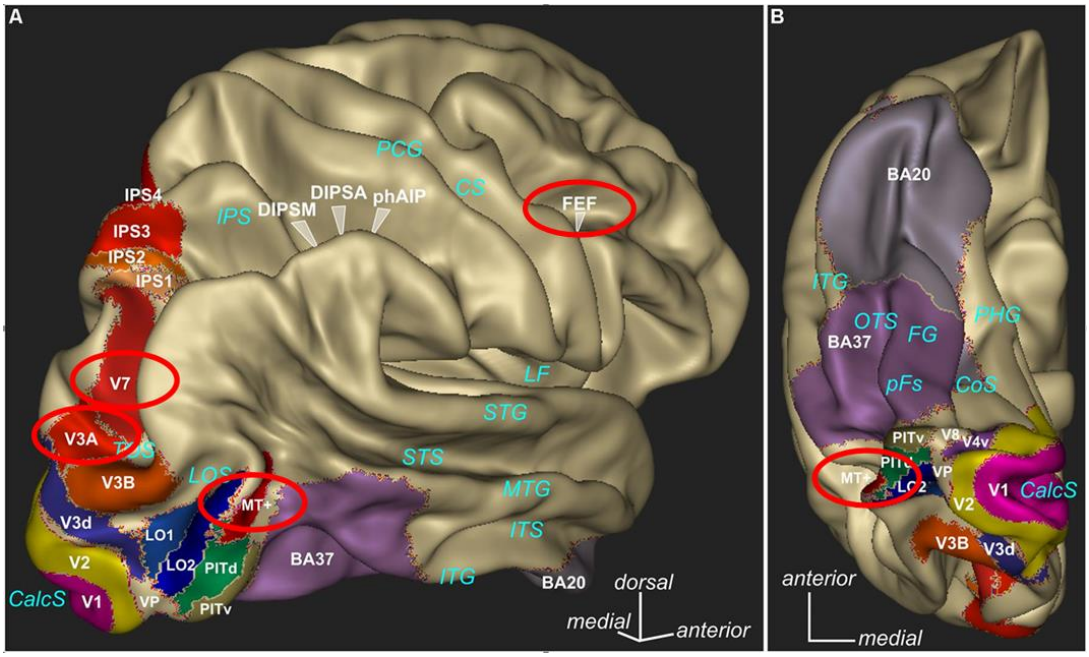

Figure 3: Different views of the brain (A, B, C), with areas of interest for 3-D vision encircled in red **[19] [20]**.

In an EEG-based study [6], 40 subjects had to visualize movie clips in 2D and in 3D, using alternative and simultaneous image projection. The EEG frequency bands that were used to monitor the subjects included delta, theta, alpha, beta and gamma frequencies. In all the aforementioned bands, based on spatial cross-correlation of EEG signals [6], higher feedback was always found for 2D than for alternative 3D technology (3DA) stimuli (further discusses in section *Side effects related to the methods that create the 3D effect*). However, there is higher feedback on

Delta-Theta-Alpha waves due to 3DP than to 2D stimuli (Table 1). We may therefore favor those waves in any EEG experiment on the 3DP technology. Lastly, the Table 2 shows the comparison of passive 3D technology (3DP) versus 3DA stimuli, emphasizing preference for 3DP activation on all lobes, with some higher Beta-Gamma feedback for 3DA on the Frontal and Pre-frontal lobes.

Frequency/Lobes	Pre-Frontal	Frontal	Central	Parietal	Occipital	Temporal
Delta (1-4 Hz)			2D	2D (P4)	2D	2D
Theta (4-8 Hz)		3DP(Fz)			3DP(O1)	
Alpha (8-12 Hz)			3DP(C4)			
Alpha-I (8-10 Hz)						3DP (T4)
Alpha-II (10-12 Hz)		3DP(Fz)	3DP	3DP		3DP
Beta (12-25 Hz)		2D				2D
High Beta (25-30 Hz)		2D				2D
Beta-I (12-15 Hz)		2D		2D		2D
Gamma (30-40 Hz)		2D				2D
High Gamma (40-50 Hz)		2D				2D

Note: The P-value is set by Bonferroni correction.

Table 1. Brain activation preference from 3DP or 2D stimuli **[6]**.

Frequency/Lobes	Pre-Frontal	Frontal	Central	Parietal	Occipital	Temporal
Delta (1-4 Hz)		3DP	3DP		3DP(O2)	3DP
Theta (4-8 Hz)	3DP				3DP	3DP
Alpha (8-12 Hz)		3DP(F7)			3DP	3DP(T4)
Alpha-I (8-10 Hz)					3DP	
Alpha-II (10-12 Hz)			3DP	3DP(Pz)		
Beta (12-25 Hz)		3DA(Fz)				
High Beta (25-30 Hz)	3DA (FP2)	3DA				
Beta-I (12-15 Hz)		3DP	3DP			
Gamma (30-40 Hz)	3DA (FP2)	3DA				
High Gamma (40-50 Hz)		3DA(F3)				

Note: The P-value is set by Bonferroni correction.

Table 2. Brain activation preference from 3DP or 3DA stimuli **[6]**.

3. CAUSES OF SIDE EFFECTS

Side effects related to the methods that create the 3D effect

Two types of 3D glasses are available on the market: passive polarized glasses and active shutter glasses [6]. Passive polarized glasses for 3D TVs are based on linear polarization, where the left and right images are presented simultaneously. In movie theaters one uses circular polarization, which offers a greater field of view for the 3D effect, but the left and right images have to be presented alternatively. In both cases, the 3D effect comes from a different polarization in the left and right eye. Active shutter glasses are synchronized with a sensor on the glasses: each eye receives an image from the screen and the corresponding shutter is opened in the glasses. This means that at every single moment, one eye can see and one eye cannot, as the shutter of the glasses for that eye is closed. The shutters of the glasses open and close about 240 times per second (speed needed for 3-D perception), which is much higher than the frame rates of non-3D movies (usually lower than 30 frames/sec).

The reported side effects (visual fatigue, motion sickness) can arise when the projected stereoscopic images are distorted [6]. When using passive 3D glasses, it is possible that an image intended for one of the eyes may be also seen by the other eye, but dim. This is called cross-talk and it occurs when the polarization in the glasses is not perfect. In 3D active glasses, the speed at which the shutter opens and closes might not be the same in the left and right lens and if the switching of images becomes too slow, the 3D visualization is not smooth anymore. Furthermore, the weight of the active shutter glasses might also be a cause of discomfort, as they are much bigger than the passive polarized ones.

The possible relationship between the desynchronization of the active alternating images and eye blinks was studied [6] in order to investigate the cause of the reported high discomfort in alternative 3D technology. The study was done over a year, using EEG on 40 subjects and the selection criteria for the subjects was to not suffer from motion sickness. It was found that a few problems arise with alternative 3D technology (3DA), because the human brain is used to decode visual information that comes to the eyes simultaneously. When using 3DA, although it seems like a certain image is seen by both eyes at the same time, the brain doesn't actually process that same image simultaneously. The processing time difference between that image seen by the left eye and the right eye can range between 1 msec and 4 msec. 3DA thus causes a deviation in the human mechanism of 3D image decoding. Furthermore, 3DA does not take into account eye blinks (each lasting 100ms), which cause a loss of 3D visualization, as multiples images are skipped. This is called de-synchronization of the eyes. Only with the next image will the eyes be able to resynchronize. Since eye blinking is repetitive, desynchronizations and resynchronizations will occur throughout the visualization, making multiple breaks in 3D visualization (i.e.: the eyes will see in 2D and 3D alternatively). Lastly, 3DA glasses or headsets are heavy, which may cause fatigue. The latter will then cause an increase in the occurrence of eye blinks and thus an increase in the number of breaks in the 3D visualization. These problems with alternative 3D technologies justify that 75% of the 40 subjects preferred passive polarized glasses [6].

Disparity tuning of neurological cells

The primary visual cortex is composed of simple cells, which respond only to light or dark stimuli, and complex cells, that respond to a mix of light and dark stimuli [21]. Both types are involved in depth perception and can be categorized as far cells, near cells or tuned zero cells. Tuned zero cells respond to retinal disparities that are on the plane of fixation (horopter, see Figure 1). Far cells respond to disparities that are further away than the plane of fixation. Near cells respond to disparities that are in front of the plane of fixation.

Cells from the primary visual cortex (PVC) in animals respond indeed selectively to objects at specific distances from the subject [7]. This corresponds to the fact that some cells respond selectively to cells located either closer or further away from the plane of fixation. Such neurons, whether far, near or zero tuned, have been located in the V1, V2, V3, V5 areas and the medial superior temporal (MST) area of the brain (see Figure 4.) [7].

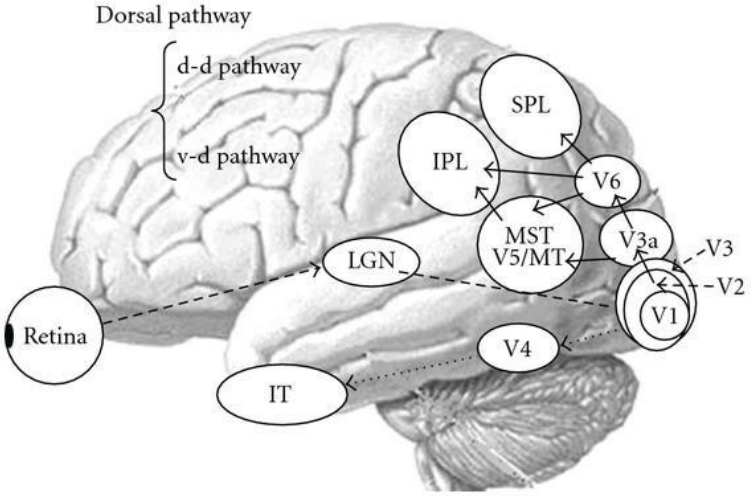

Figure 4. Positions of V1-V5 and MST on the brain **[22]**.

For experimental 3D investigation, it would also be good to know how those neurons are clustered to specific areas. The MT area was chosen to be further studied and it was determined that neurons are clustered according to the disparities they are tuned to in that region [7]. It was also found that these neurons have a columnar organization (neurons clustered in columns). This approach allowed to analyze the role of MT neurons in depth perception. It was also confirmed that by electrically microstimulating neural columns, neurons can be biased toward their preferred disparity.

4. VIRTUAL REALITY

Immersion in Virtual Reality (VR) can lead to similar side effects as for typical immersion in a 3D environment. The symptoms include an increased heart rate, dizziness and nausea [23]. The aforementioned symptoms are related to motion sickness induced by the virtual environment (or cybersickness). The *sensory conflict theory* was elaborated to explain the origin of motion sickness [24]. This theory is based on the hypothesis that neural signals that originate in the brain area responsible of spatial orientation can cross talk to other brain areas, leading to sickness

symptoms [24]. Neurons responsible of the erroneous communication between areas have not yet been physiologically identified [24]. However, when immersed in a VR environment, subjects experienced an EEG power increase of 8-10Hz in the parietal and motor areas of their brain and some of them also experienced an increase of 18-20Hz in their synchronized responses recorded in those areas [25].

Motion sickness is a condition where signals coming from the eyes, the vestibular system and the non-vestibular proprioceptors (sensory receptors responding to position and movement) are conflicting with each other [26]. Moreover, they are conflicting with previous similar interactions with the environment. This implies the existence of two neurological units: one, called the neural store, which retains information regarding previous neural signals from spatial senses and one that compares the current input coming from the spatial senses with those in the neural store. According to the original definition of the theory (Reason & Brand, 1975) [26], motion sickness thus results from current information conflicting with the information expected from the contents of the neural store. This means that, for instance, the brain knows that when eyes perceive movement, the body should perceive movement as well. However, in artificial 3D, the eyes and body do not send concurring messages to the brain. This mismatch produces neural signals whose magnitudes determine the severity of motion sickness [26]. Furthermore, according to the sensory conflict theory, more recent sensory inputs update the old ones, so that mismatched inputs can replace the correct ones in the neural store. This means that with continual exposure to situations causing motion sickness, an individual should experience less and less sickness. If the subject makes no movements during a situation, then sensory information alone updates the neural store [26]. If movements are involved, then the new sensory information is stored as well as the efferent movement involved. Oman (1982) presented a quantified version of the theory by developing a mathematical equation describing the difference between the expected sensory input and the actual one [26]. Moreover, according to him, there is always some level of conflict in everyday life, but symptoms are not necessarily noticed.

The 3D and VR technologies do not only come with sickness issues, but they also have the potential to solve some health problems. For example, stereo-blind people may recover stereo vision by watching 3D movies [27]. Also, training an eye affected by amblyopia (“lazy eye”) can be more easily done with 3D technologies [28]. There is also a wide range of neurorehabilitation set-ups for training in a VR environment while getting real-time BCI feedback [29] [30].

5. CONCLUSION

The increase in 3D and VR users has led to increasing complaints about side effects such as tired eyes, headaches, nausea and disorientation. The immediate response to these complaints was for the 3D-technology companies to warn children, elders and pregnant women against immersions in 3D or VR. At the same time, social and medical studies are initiated in order to understand what makes people more or less prone to experiencing these side effects.

It was found that an individual’s interpupillary distance (IDP) plays a role in stereoscopic vision. A small IDP leads to an increased stereoscopic vision, and thus an increase in the perception

of stereoscopic screen disparity. Moreover, conflict in vergence and accommodation caused by artificial 3D leads to visual fatigue and to difficulty in viewing the 3D effect. Concerning the location of the processes leading to stereoscopic viewing in the brain, fMRI experiments showed an increased cortical activation of the FEF and V3A areas. The neurons involved in stereoscopic vision are far-tuned or near-tuned, which means they only respond to stimuli *further away* or *in front of* a plane of fixation. These neurons have a columnar organization and they can be biased toward their preferred disparity by microstimulation of the neural columns. Furthermore, EEG experiments showed higher feedback in 2D than in 3D. When using passive 3D glasses, cross-talk between the left and right images can lead to imperfections in stereoscopic vision. With 3D active glasses, there can be desynchronization and slow-down of the shutter speed for the left and the right eye. Eye blinks can be a cause of desynchronization in the left and right image processing.

Regarding immersion in Virtual Reality, motion sickness is one of the main side effects, which can be explained with the sensory conflict theory. This theory states that motion sickness results from current information conflicting with the information expected from the contents of a neural store. The neural store is a collection of information concerning previous signals coming from the spatial senses. This mismatch between the new and the expected signals leads to neural signals causing motion sickness. However, with continuous exposure to the new signals, the latter can eventually update the old ones. This means that with time, the user may become more comfortable with the 3D technology. VR (and 3D) environments can also be used beyond entertainment, for applications such as neurorehabilitation.

For further understanding of the side effects coming from VR or 3D immersion, it would be necessary to find a way to quantify the feedback of sickness (for example using BCI, measuring the heart rate, skin resistance, etc.) according to the different sources of error in the 3D effect (IDP, cross-talk, distance from the screen, frame rate, etc.). For instance, an increase in the frame rate (1-4 msec/frame, meaning more than 250 frames/sec) could lead to an improvement of the stereoscopic viewing. In order to assess the acceptable level of 3D video quality, the user feedback should be also quantified for different levels of cross talk or desynchronization between the left and the right eye videos. Particularly for VR, it would be interesting to quantify the brain feedback with respect to the disparity between body movement and visual movement perception.

RÉFÉRENCES

[1] What Is, "Definition: Virtual Reality," May 2015. [Online]. Available: http://whatis.techtarget.com/definition/virtual-reality. [Accessed 6 February 2016].

[2] Dictionary, "Virtual Reality," 2016. [Online]. Available: http://dictionary.reference.com/browse/virtual-reality. [Accessed 6 February 2016].

[3] A. G. Solimini, A. Mannocci, D. D. Thiene and G. L. Torre, "A survey of visually induced symptoms and associated factors in spectators of three dimensional stereoscopic movies," *BMC Public Health,* vol. 12, no. 1, pp. 1-11, 2012.

[4] D. Kim, Y. J. Jung, E. Kim, Y. M. Ro and H. Park, "Human brain response to visual fatigue caused by stereoscopic depth perception," *Digital Signal Processing (DSP), 2011 17th International Conference on,* pp. 1-5, 2011.

[5] D. Hurst, "How watching 3D films can be bad for your brain," 5 May 2010. [Online]. Available: http://www.dailymail.co.uk/health/article-1271618/How-watching-3D-films-bad-brain.html. [Accessed 31 August 2015].

[6] A. S. Malik, R. N. H. R. Khairuddin, H. U. Amin, M. L. Smith, m. Kamel, J. M. Abdullah, S. M. Fawzy and S. Shim, "EEG based evaluation of stereoscopic 3D displays for viewer discomfort," *BioMedical Engineering OnLine,* vol. 14, no. 1, pp. 1-21, 2015.

[7] R. D. Freeman, "Stereoscopic vision: Which parts of the brain are involved?," *Current Biology,* vol. 9, no. 10, p. R610–R613, 1999.

[8] Samsung, "Samsung Gear VR: User Manual," [Online]. Available: http://downloadcenter.samsung.com/content/UM/201510/20151009012011714/GEN_SM-R320_GEAR-VR_EN_UM_LL_FINAL_AC.pdf. [Accessed 20 July 2015].

[9] M. Lambooij, W. IJsselsteijn, M. Fortuin and I. Heynderickx, "Visual Discomfort and Visual Fatigue of Stereoscopic Displays: A Review," *Journal of Imaging Science and Technology,* vol. 53, no. 3, pp. 1-14, 2009.

[10] S. YW, O. J, K. HM, C. YA and S. JS, "Three-dimensional display-induced transient myopia and the difference in myopic shift between crossed and uncrossed disparities," *Investigative Ophthalmology & Visual Science,* vol. 53, no. 8, pp. 5029-5032, 2012.

[11] G. Heiting, "How Your Vision Changes as You Age," All About Vision, January 2016. [Online]. Available: http://www.allaboutvision.com/over60/vision-changes.htm. [Accessed 5 January 2016].

[12] G. D. Love, D. M. Hoffman, P. J. Hands, J. Gao, A. K. Kirby and M. S. Banks, "High-speed switchable lens enables the development of a volumetric stereoscopic display," *Optics Express,* vol. 17, no. 18, pp. 15716-15725, 2009.

[13] N. Qian, "Binocular Disparity and the Peception of Deapth: Review," *Neuron,* vol. 18, pp. 359-368, 1997.

[14] R. Zenz, "Horopter," Wikipedia: The Free Encyclopedia, 29 July 2015. [Online]. Available: https://en.wikipedia.org/wiki/Horopter. [Accessed 7 August 2015].

[15] M. Urvoy, M. Barkowsky and P. L. Callet, "How visual fatigue and discomfort impact 3D-TV quality of experience: a comprehensive review of technological, psychophysical, and psychological factors," *Annals of Telecommunications,* vol. 68, no. 11, pp. 641-655, 2013.

[16] A. Hunter, "Vergence-accommodation conflict is a bitch—here's how to design around it.," Vrinflux, 9 November 2015. [Online]. Available: http://vrinflux.com/vergence-accommodation-conflict-is-a-bitch-heres-how-to-design-around-it/. [Accessed 7 December 2015].

[17] H. R. Rodman and T. D. Albright, "Single-unit analysis of pattern-motion selective properties in the middle temporal visual area (MT)," *Experimental Brain Research,* vol. 75, no. 1, pp. 53-64, 1989.

[18] J. A. Perrone, "A visual motion sensor based on the properties of V1 and MT neurons," *Vision Research,* vol. 44, no. 15, pp. 1733-1755, 2004.

[19] Studyblue, "The Visual System," University of Alberta, [Online]. Available: https://www.studyblue.com/notes/note/n/the-visual-system/deck/1317678. [Accessed 19 September 2015].

[20] O. Joly and E. Frankó, "Neuroimaging of amblyopia and binocular vision: a review," *Frontiers in Integrative Neuroscience,* vol. 8, no. 62, 2014.

[21] L. M. Martinez and J.-M. Alonso, "Complex Receptive Fields in Primary Visual Cortex," *Neuroscientist,* vol. 9, no. 5, pp. 317-331, 2003.

[22] T. Yamasaki, H. Muranaka, Y. Kaseda, Y. Mimori and S. Tobimatsu, "Understanding the Pathophysiology of Alzheimer's Disease and Mild Cognitive Impairment: A Mini Review on fMRI and ERP Studies," *Neurology Research International,* vol. 2012, pp. 1-10, 2011.

[23] S. Ali, S. Vaughn and J. Williams, "Oculus Rift: Physiological and Psychological Effects of Virtual Reality," Medium, 9 April 2015. [Online]. Available: https://medium.com/oculus-rift/6-physiological-and-psychological-effects-of-virtual-reality-9bc3aee94868#.2mdd0xgki. [Accessed 12 July 2015].

[24] O. CM, "Motion sickness: a synthesis and evaluation of the sensory conflict theory," *Canadian Journal of Physiology and Pharmacology*, vol. 68, no. 2, pp. 294-303, 1990.

[25] C.-T. Lin, S.-W. Chuang, Y.-C. Chen, L.-W. Ko, S.-F. Liang and T.-P. Jung, "EEG Effects of Motion Sickness Induced in a Dynamic Virtual Reality Environment," *Conference Proceedings: Annual International Conference of the IEEE Engineering in Medicine and Biology Society,* pp. 3872-3875, 2007.

[26] L. Warwick-Evans and S. Beaumont, "An Experimental Evaluation Of Sensory Conflict Versus Postural Control Theories Of Motion Sickness," *Ecological Psychology,* vol. 7, no. 3, pp. 163-179, 1995.

[27] B. Bridgeman, "Restoring Adult Stereopsis: A Vision Researcher's Personal Experience," *Optometry and Vision Science,* vol. 91, no. 6, pp. e135-e139, 2014.

[28] A. Gargantini, M. Bana and F. Fabiani, "Using 3D for Rebalancing the Visual System of Amblyopic Children," *2011 International Conference on Virtual Rehabilitation,* pp. 1-7, 2011.

[29] S. B. i. Badia, H. Samaha, A. G. Morgade and P. F. Verschure, "Exploring the Synergies of a Hybrid BCI – VR Neurorehabilitation System: Monitoring and Promoting Cortical Reorganization Through Mental and Motor Training," *2011 International Conference on Virtual Rehabilitation,* 2011.

[30] IEEEXplore: Digital Library, "Virtual Rehabilitation (ICVR), 2011 International Conference on," IEEEXplore: Digital Library, June 2011. [Online]. Available: http://ieeexplore.ieee.org/xpl/mostRecentIssue.jsp?punumber=5959357. [Accessed 2 January 2016].