Stereoscopic Image Visual Perception

Krzysztof Fornalczyk, Piotr Napieralski, Dominik Szajerman, and Adam Wojciechowski

***Abstract*—Stereoscopic films and interactive presentations are extensively popularized whereas their perceived quality still dissatisfies viewers. The reasons are shared between hardware inconsistencies and stereo image producers unawareness concerning factors influencing depth perception quality. This paper reviews aspects influencing 3D image perception visual comfort, presents visual comfort estimation methods and suggests how to measure image perception quality. It also comprises results of researches conducted on dedicated CinemaVision Movie Diagnostics work stand.**

***Index Terms*—stereoscopic image; image quality factors; perception convenience; visual fatigue.**

I. Introduction

HUMAN vision system is the most valuable and reliable source of information concerning surrounding world coming indirectly to observers' brain (about 80% of all human body sensors stimuli [1]). Objects' colors, shapes, surfaces factures, interrelations and their movements are registered by human eyes and consequently perceived and interpreted as spatial visual experiences. Three dimensional scene experience can be available also due to sophisticated techniques providing human eyes with stereo pair of images recorded by real or virtual stereo cameras. Unfortunately current techniques, even professional ones, do not respect all the depth perception factors characterizing real spatial image. Furthermore probable stereo cameras' inconsistencies and film production errors further drastically may decrease the visual comfort.

Provided paper aggregates all main factors influencing stereoscopic image perception quality and puts attention to most common errors and artifacts of the stereoscopic material production process. It suggests how stereoscopic image quality, from the human perception (visual fatigue) point of view, can be measured and describes experimental testing environment that was used for testing professional stereo material in relation to users perceived impressions.

II. Factors Affecting Stereoscopic Image Perception

Among several factors affecting stereo image perception quality three main groups can be distinguished according to the origin of artifacts. First group is connected with hardware and technology inherent parameters, second group encompasses cameras settings that should be possibly correlated with a human visual system behavior and third concerns parameters of the content presented in the image and its motion (fig. 1).

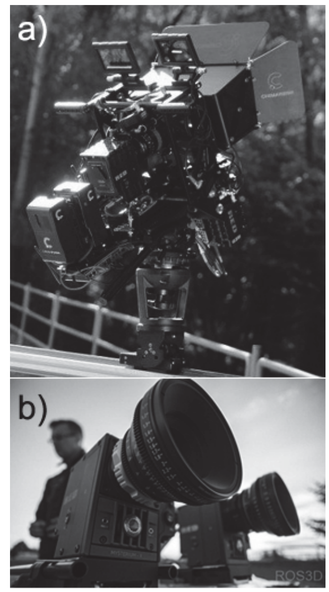

Fig. 1. CinemaVision stereoscopic rigs: a) perpendicular; b) parallel.

The first group of presented factors is more hardware and technology dependent and it just faintly depends on camera operators. Discrepancies between left and right eye dedicated images perceived as binocular asymmetry in geometry, luminance, color or focus, cause that each eye percepts image aberrations. Moreover they do not correspond with human vision system and result in visual discomfort (fatigue) (fig. 2).

Fig. 2. Discrepancies between left and right eye images; (upper stereo pair from Resident Evil) asymmetry in luminance; (bottom stereo pair fragment from Galapagos: The Enchanted Voyage) asymmetry in sharpness [52].

K. Fornalczyk, P. Napieralski, D. Szajerman and A. Wojciechowski are with the Institute of Information Technology, Lodz University of Technology, ul. Wólczańska 215, 90-924 Lodz, Poland (e-mail: adam.wojciechowski@p.lodz.pl)

Technological problems of left/right images separation (crosstalk) also affect depth perception as two eyes' dedicated images are registered unexpectedly as ghost objects. Additionally viewing conditions, such as limited screen size or inappropriate distance to the screen with its borders falling into field of view, may also decrease visual comfort as presented depth is unintentionally trimmed in an unnatural way. The "frame effect" occurs when objects positioned in front of the screen approach the screen frame. Stereoscopic display screens' characteristics are also a source of very well-known and studied visual fatigue factors caused by inconsistency between accommodation and convergence (fig. 3). Inconsistency between accommodation and convergence occurs when the focus point (accommodation) is not fixed on the screen plane, nondependent of the convergence point which is derived from the disparity of the signals. Uncoupling convergence and accommodation required by 3D displays frequently reduces one's ability to fuse the binocular stimulus and causes discomfort and fatigue for the viewer. This discrepancy between accommodation and convergence demand may be highly stressful for the visual system.

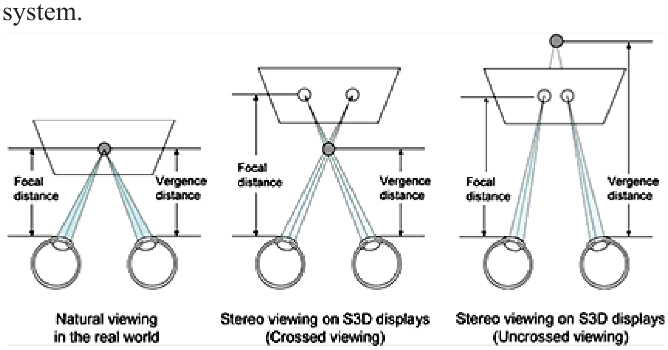

Fig. 3. Accommodation and convergence conflict. Convergence follows perceived object depth whereas accommodation remains at the screen surface [20].

Second group of factors encompasses discordance between human visual system parameters and simulating them corresponding cameras' settings (i.e.: horizontal (base) distance, convergence, depth of field) adjusted by the rig operator. This group comprises valid and operator's dependent key aspects and will be further thoroughly studied.

The first and probably the most obvious factor influencing perception is cameras' horizontal separation (cameras' base distance) that should reflect viewers' inter ocular distance (IOD). As among human races and people age IOD differs, there is no chance to theoretically satisfy all viewers with one universal camera distance. On the other hand it is usually assumed that average population inter ocular distance is 65 mm and most researchers treat it as a reference value [2]. Some interactive stereoscopic applications let the user adapt IOD to personalize the view.

Subsequent factor that should be taken into consideration is cameras' convergence reflecting human visual system point of interest - eyes fixation. People exploring their field of view fix their gaze on certain points (objects) in space (horopter). Eye bulbs are naturally rotated until the object is positioned on the main visual track of the eye. As a result physiological parallax of the observed objects (scene corresponding points retina displacement – fig. 4) is registered and transformed into the perceived scene depth. Eyes convergence is accompanied by automatically performed accommodation process which technically is simulated by camera focus.

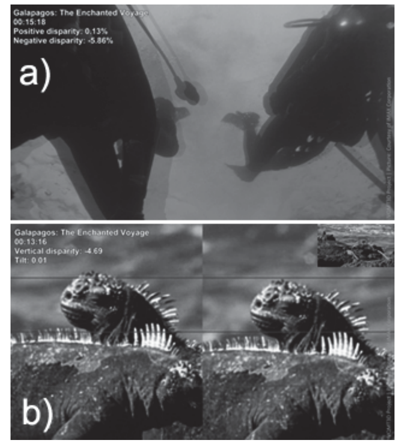

Fig. 4. a) horizontal parallax/disparity (base dependent); b) vertical disparity [52].

Unfortunately during natural scene observation human gaze very dynamically changes its fixation point (scanning path, saccades, etc.). Whereas it is almost unavailable for regular cameras recording system which is usually fixed or eventually slightly adjustable for the selected shot or the scene. Cameras' operators have to guess or even suggest what the viewer might be interested in. It may not only not suite all the viewers but several production or post-production errors (convergence-focus inconsistency, vertical disparity) may affect the final experience as well. Wide range of camera parameters decorrelation frequently results in not physically valid stereoscopic material.

It must be also mentioned that human beings limited depth ability [3] inclines operators to experiment with cameras base distance and their convergence as to enlarge presented scene depth and make the production more immersive. Whereas unconstrained and neither physically nor technically justified parameters (i.e. size of the display screen) become a source of many destructive and uncomfortable settings forcing cross-eye or divergent squint.

The third group of factors affecting stereoscopic scene perception is connected with presented content. Appropriate objects appearance, their contrast with background and relative movement should reflect real environment situations. Especially artificially rendered objects and their programmed animations are susceptible to inconsistency with reality. These aspects, affecting visual comfort, require separate investigation and are not discussed in this paper.

III. VISUAL COMFORT TESTING METHODS

Visual comfort is closely connected with visual fatigue (tiredness, headaches, and soreness of the eyes). However visual comfort can be considered in relation to the objective indicators of visual fatigue [4, 5] and subjective signs accompanying visual discomfort. Subjective indicators measurement methods may be described by the human perceptual opinion (Quality of Experience). International Telecommunication Union [5] has recommended methodology for the subjective assessment of the quality of television pictures. They proposed two classes of subjective assessments: quality and impairment assessments. They also described specific environmental conditions, for this type of indicators. Subjective measurement methods of visual comfort include subjective self-assessments such as assessment scales and questionnaires. Simultaneously various objective evaluation methods of fatigue have been proposed and different devices, like brain activity measures (EEG, fMRI) as well as optometric and galvanic skin response (GSR) instruments, were widely used.

A. *Subjective Measurement Methods*

Binocular asymmetry may be measured both by subjective and by the objective methods as well. There are three categories of the binocular asymmetries (color, geometry, luminance). First mismatch is known as the binocular color fusion limit. Subjective experiments to measure the color fusion limit use single stimulus assessment [6,7]. Zhao at al. [8] proposed a difference model based on two psychophysical experiments by modeling and incorporating the binocular combination of injected noises, luminance masking and contrast masking in binocular viewing. This model measured the perceptible distortion threshold of stereoscopic images for binocular vision. Geometry mismatches are based on asymmetrical optical geometry (e.g., image shift, rotation, magnification) [9,10]. Geometry mismatches, when the head is rolled relative to the display, were made by behavioral experiments in which authors simulated head roll by rotating the stereo display [11]. Binocular asymmetry of brightness combination [12] occurs when the input brightness is asymmetric in both eyes. This phenomenon appears when a bright light has reached one eye and a less bright (dim) light was shown to the other eye. 2D image quality metric (e.g. PSNR) cannot be directly applied to test these asymmetry. This statement can be verified by the low correlation between the computed objective measures and the subjectively measured mean opinion scores. Experimental results of researchers from National Taiwan University [12] have shown that significant consistency could be reached between the measured mean opinion scores and the Binocular Frequency Integration-based metrics.

Another source of viewing discomfort associated with subjective visual comfort assessment method is cross talk. In a perfect stereoscopic display, the one eye image should be perceived by the dedicated eye only and should be completely invisible to the other eye. Total separation of eye images is often impossible. Cross talk produces ghosting effects and is a potential cause of headaches [13]. Pastor at al. established visibility thresholds for cross talk using a system with perfect left/right image separation (a high resolution mirror stereoscope; the experimental conditions were generated with image processing techniques). Subjective tests revealed that visibility of cross talk increases with contrast and increasing binocular parallax (depth) of the stereoscopic image. In this situation, reason of viewing discomfort is that range of DOF concurs with the range of fusion.

Kim et al. [14] investigated the effect of convergence–accommodation conflict and parallax difference on binocular fusion for random dot stereograms. They measured the time required for fusion under various conditions that include foreground parallax, background parallax, focal distance, aperture size, and corrugation frequency. They found the relationship between fusion time and visual fatigue by conducting a subjective evaluation of stereoscopic images.

Visual comfort received local low evaluation scores for scenes with high degrees of screen disparity and high amounts of motion [15]. Experiments confirmed that discrete changes of motion in the depth direction cause significant decrease of visual comfort [16]. Experiments have shown that visual fatigue was not a serious problem when still stereoscopic images, which were only perceived by convergence eye movement, were displayed within the corresponding range of the depth of focus. It was also found that visual fatigue occurred when the stereoscopic images involving the depth motion component were displayed, even if they were shown within the range of the depth of field. Based on the subjective measurement methods, it was tested that binocular disparity induced visual discomfort [17]. Authors used two subsets of comfort videos and discomfort videos for the subjective assessment of visual comfort. After collecting all subjective ratings, mean opinion score (MOS) of visual comfort was calculated for each video stimulus. Subjective evaluation can be used to quantify the level of visual discomfort and fatigue. Subjective measurement methods evaluation were used to estimate the level of discomfort, as it is a subjective phenomenon by nature [18,19,20]. These measures are more encumbered with errors affected by individual variation of human visual fatigue.

B. *Objective Measurement Methods*

Objective measurement methods can obtain information about the level of visual and cognitive fatigue with optometric and brain measurement devices [18].

Optometric measurements were used to verify the physiological parameters of human vision, such as changes in the accommodation-convergence function, pupil size, and blinking rate [19, 20, 21, 22].

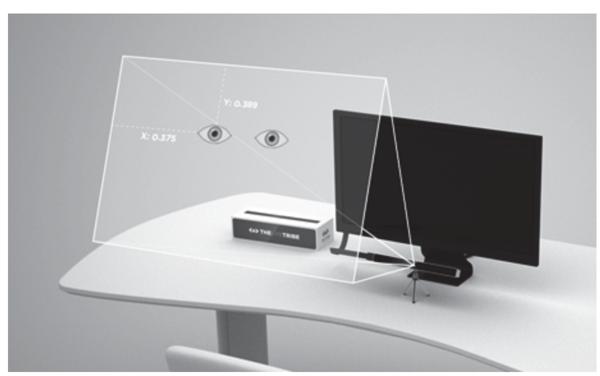

Fig. 5. Optometric instrument (The Eyetribe Tracking System) to perform measurement of stereoscopic movies.

Optometric instruments are available to perform the objective measurements of changes in the dynamics of the eyes like: pupil diameter, gaze tracking or blinking rate. The eyes are illuminated with an infrared light pattern and when reflected it is registered and analyzed. In this manner, the changes in the physiological parameters of the eyes in response to a specific stimulus can be dynamically recorded (fig. 5).

Accommodation-convergence conflict [23] was tested with optometric instruments [24, 22]. Jansen at al. used 2D and 3D natural and noise images to investigate the effect of additional binocular information on basic eye movement. They found a correlation between disparity and the selection of fixation points and change in basic eye movement properties when disparity information was present. Autorefractor [25, 26] was used to allow objective, continuous, open-field measurements of accommodation and pupil size for the investigation of the visual response to real-world environments and their dependence on changes in the optical components of the eye. Brain activity measures (EEG, fMRI) may estimate cognitive fatigue underlying 3D visual fatigue. Functional magnetic resonance imaging (fMRI) was used for the objective measurement to assess the human brain regions involved in the processing of the stereoscopic stimuli with excessive disparities [17]. The subjective measurement results, were used to find subsets of comfort and discomfort videos. Then, a fMRI experiment was conducted with the subsets of comfort and discomfort videos in order to identify which brain regions were activated while viewing the discomfort videos in a stereoscopic display. 3D visual fatigue was also measured by background EEG and ERP signals [27, 28, 29]. Power of beta frequencies increased as watching duration increased and it was much stronger in 3D rather than in 2D condition. More importantly, P700 delayed as watching duration increased as well as in 3D rather than in 2D conditions. Similar pattern of results was obtained in the measured subjective 3D visual fatigue.

Visual comfort assessment is playing an important role for stereoscopic safety issue. Ye Bi and Jun Zhou [30] proposed visual comfort assessment metric that utilized interest salient motion regions where human subjects focus on. To achieve better performance, this approach combined salient cues, motion cues with depth cues in order to extract salient motion regions in consideration of depth context. The experimental results have demonstrated that proposed visual comfort assessment improves the correlation with the subjective assessment. The “Video Quality” scale is a very complex problem and the Quality of Experience (QoE) of 3D video is a multidimensional concept and therefore more than one scale is in many cases needed for subjective assessment of the QoE of 3D video [31].

Measurement of visual discomfort can be performed using the tracking physiological response of the observer. Such reactions may include eye pressure, blink frequency or eye movement.

IV. Measuring Visual Fatigue and Discomfort of 3D Images Perception

The quality metric to measure impaired stereoscopic video is still a popular research area [32, 33, 34, 35]. A visual comfort metric for stereoscopic 3d video quality is still in its early stage, as 2D image quality metrics are useless for 3D images [36, 37, 38]. For measuring the perceived quality of stereoscopic images, several metrics have been proposed by integrating 3D perceptual properties. Da Silva et al. [32] made a statistical analysis of two subjective experiments conducted to analyze the quality assessment techniques for compressed stereoscopic video. This metric and the subjective results database are publicly available, for the 3D media delivery systems. Xing et al. [38] proposed quality evaluation of crosstalk perception on polarized stereoscopic display. Kulyk et al. [31] proposed quality assessment with multi-scale subjective method based on state-of-the-art physiological and psychological understanding of the human visual system. Juszka et al. [39] proposed an objective, bit stream quality metric for stereoscopic high definition video affected by compression and packet loss in a network. Ryu et al. [40] proposed stereoscopic image quality metric based on binocular perception model for stereoscopic images model considering asymmetric property of a stereoscopic image pair. Experiments for publicly available databases show that the proposed metric provides consistent correlations with subjective quality scores. Subjective evaluations of 3D image were conducted to investigate the influences of 3D factors to a perceived quality of 3D image. In order to measure an objective quality of a stereoscopic image, several full-reference quality metrics have been proposed using the fusion of 2D quality metrics and depth distortion [41, 42]. Measured depth acuity is slightly higher after 3D viewing than after 2D viewing [43]. Visual fatigue is related to many different aspects of the human visual system. Visual discomfort is more subjective and almost all studies evaluating discomfort by questionnaires provided significant indicators for measuring visual fatigue. These questionnaires were based on potential symptoms or source of visual discomfort and asked the viewers to identify more precisely the source of their discomfort [20, 24]. Researchers have proposed many approaches which usually use global statistics for stereoscopic 3D video visual comfort assessment [44, 45, 46]. They use a continuous evaluation of visual comfort similar to the Single Stimulus Continuous Quality Evaluation (SSCQE) method [5]. They have found differences in terms of individual’s tolerance of visual discomfort and fatigue. These differences are linked to some normal differences in visual processes or to some form of stereo-anomaly. This generated problems for flexible and correct metrics. For example accommodation ability and maximum pupil diameter decline with age. The maximum pupil diameter reduces from 8 mm over 6 mm to approx. 2...3 mm [47]. Individual differences are the main problem for the definition of general and easily applicable indicators of visual fatigue and visual discomfort. Reichelt et al. [47] proposed measuring image quality and visual comfort with the depth cues of the human visual perception. Their analysis were based especially on near-range depth cues and compared visual performance and depth-range capabilities of stereoscopic and holographic displays. They have proposed a “safety depth zone” for stereo displays, which had to compromise considerably on utilizable depth. Lambooij et al [4, 15] have defined visual fatigue as physiological strain or stress resulting from excessive exertion of the visual system. They applied visual fatigue for objectively measurable symptoms for a stereo comfort zone. They have appointed indicators, both objective and subjective, for measuring visual fatigue and visual discomfort associated with 3D displays. Jae Gon Kim et al. [48] have also researched on visual fatigue and visual discomfort with displays. They proposed Simplified Relative Visual Fatigue model to evaluate the degree of the visual fatigue in a stereoscopy. They considered “accommodation and convergence” factors that can be calculated by disparities in a stereoscopy. Song-Pei et al. [49] proposed metric of visual comfort for stereoscopic motion. Based on measurements of the visual discomfort and caused by motion in stereoscopic content, a metric was proposed to evaluate the level of comfort associated to viewing short stereoscopic videos. This is important that visual comfort metrics had the correlations with subjective judgment. Visual comfort metrics that quantify the level of visual discomforts are very important for sustainable development of stereoscopic videos in future.

V. Work Stand for Perception Based 3D Image Visual Fatigue Evaluation

Authors have designed the test bench allowing to examine the eye reaction of the tested person (fig. 6).

Fig. 6. Original project of optometric instrument (CinemaVision Movie Diagnostics) to perform measurement of stereoscopic movies.

It is composed of The Eyetribe sensor which is responsible for the user gaze point tracking and wearable part – polarized glasses with micro video camera mounted on – responsible for detection blinking rate and pupil diameter monitoring. Though eye tracker vendors claim that the device is capable to retrieve pupil diameter and blink rate the obtained results, though filtered [50], did not reflect reliably eyesight biomechanics. That is why the decision regarding additional wearable camera was made. Additionally mouse controller is used to let the tested person mark any remarkable moments which should be next explained within a questionnaire. These three biomechanics factors were identified as functional indicators influencing observers’ visual fatigue/comfort in 3D films watching context. Supplementary introspection was introduced to collect descent explanation of experienced moments.

Experimental tests have revealed that elaborated work stand reliably reflected gaze point, but retrieving gaze pointed content characteristics still requires manual image analysis. Therefore the work stand will be further developed in order to automate stereoscopic image analysis as to find out possible correlations between users’ biomechanics accompanied with biophysical reactions and corresponding image quality characteristics. The goal of forthcoming researches is to elaborate non-reference automatic 3D image quality metric which has a human visual system background. Then it can be applied for boosting and optimizing highly expensive 3D films making process.

VI. Stereoscopic Image Visual Perception Evaluation Tests

Evaluation tests were performed on 35 people, aged between 30 and 50. They were selected and invited to the evaluation tests as to satisfy two diverse categories: both genders and versatile stereo image operation experience.

Tested people were provided with a dedicated CinemaVision video advert (https://youtu.be/3H8sjEP0CwY) lasting 2:16 minutes, composed of 34 shots, presenting different components of the system. The film was displayed on a 50 inches LG TV screen with passive image polarization and CinemaVision Movie Diagnostics eye tracking component positioned about 1 meter in front of the spectator, in a place not occluding the screen, and GoPro camera recording the experiment from above the TV screen. Key points were marked with a mouse button pressed while watching the movie.

Besides automatic biomechanical reaction monitoring, the people were asked to fill in a questionnaire. Its role was to retrieve, besides personal details, information regarding the shots and scenes evoking characteristic expressions, both positive and negative.

Initially discomfort evoking shots were analyzed (fig. 7).

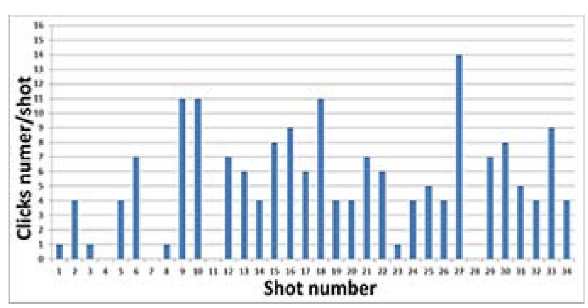

Fig. 7. Discomfort clicks quantity per shot.

It has appeared that shots number 27 and subsequently 9, 10 and 18 received the highest quantity of discomfort marks. In fact mainly due to existing compression artifacts.

In the next step spectators' pupil diameter was analyzed (fig. 8).

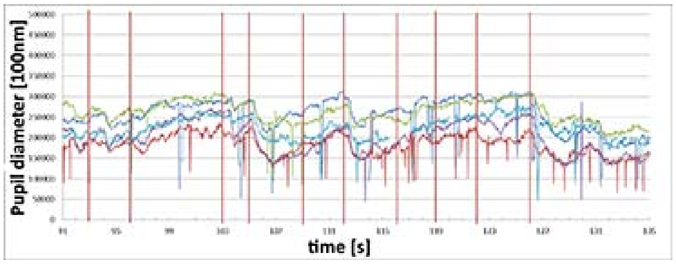

Fig. 8. Pupil diameter for 5 selected spectators within last 45s of the analyzed video material.

It has appeared that among different spectators pupil diameter changes were visually consistent (fig. 8) though each of the viewers had individual (personal) base pupil size. Pupil size changes appeared mainly when scenes with high contrast and rapid illumination changes were presented to the viewers. Shots no. 2, 5, 8, 9, 12 and 13 were recorded as mainly affecting pupil diameter. It was caused mainly by sudden illumination changes (shot 2 and 5) or by natural accommodation-vergence eye-sight reactions (shot 9, 12 and 13). As contrast/illumination changes evoked natural, bio-physiological consistent reactions, eyesight convergence (depth) following accommodation can generate a hypothesis concerning gaze horopter depth evaluation within a scene. Then pupil size considerable variance should be previously solved. On the other hand there were no conclusions, regarding visual fatigue, withdrawn basing on pupil diameter analysis.

Finally gaze point analysis researches were conducted. Spectators gaze points were registered by means of eye tracker at a frequency of 30 Hz, thus only fixation points were registered rather than saccades. It has appeared that gaze fixation points were consistent mainly with frames composition rules. Spectators concentrated mainly on human postures, their faces, big objects, brighter regions and frame diagonal crossing composition points.

The last monitored aspect was blinking rate, described as determinant of visual comfort [51]. In the figure 9 exemplary blinking rate per shot is presented.

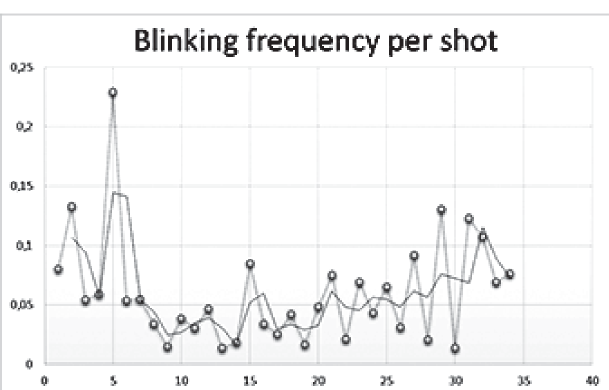

Fig. 9. Exemplary blinking frequency for selected person.

Blinking rate frequency analysis has revealed that it strongly depends on viewers personal abilities and ones concentration on performed task (surveying stereo image quality). Moreover researches have revealed big variance of the results and low correlation with video material. It was probably caused by the characteristics of the tested video material - dynamic (less then 4s per shot) video advertisement composed of changeable views.

VII. Conclusion

One of the goals of conducted studies was to investigate the aspects influencing 3D image perception visual comfort and suggest how to verify image perception quality as well as provide measures correlated with dedicated eye tracking experiments. Overall results revealed great potential of researches basing on viewers' biomechanical and bio-physiological reactions and their application in the stereo image quality/perception evaluation studies.

Future research will be focused on measuring a quality of stereoscopic images and comparing obtained results with other existing metrics. We plan to extend our research to establish guidelines for stereoscopic videos tests to determine objective quality assessment metrics for 3D. The researches have already originated with the advanced visual perception testing work stand elaboration which is currently developed as the CinemaVision Movie Diagnostics tool.

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References

[1] H.W. Randolph Blake, "Binocular vision," Vision Res. National Institutes of Health, vol. 51, pp. 754–770, 2011.

[2] N.A. Dodgson, "Variation and extrema of human interpupillary distance," Proc. SPIE, vol. 5291, pp. 36–46, 2004.

[3] I. Howard, Perceiving in Depth. Oxford University Press, 2012.

[4] I.H. Marc T.M. Lambooij, Wijnand A. IJsselsteijn, "Visual discomfort in stereoscopic displays: A review," Stereoscopic Displays and Virtual Reality Systems XIV, vol. 6490, pp. 6490–6503, 2007.

[5] I.T. Union, "Subjective methods for the assessment of stereoscopic 3dtv systems," Recommendation ITU-R BT.2021, Tech. Rep.

[6] Y.J. Jung, H. Sohn, S. il Lee, Y. M. Ro, and H. W. Park, "Quantitative measurement of binocular color fusion limit for non-spectral colors," Opt. Express, vol. 19, no. 8, pp. 7325–7338, Apr 2011.

[7] M. De Mattiello, A. Biondini, and H. Salinas, "English Dichoptic color mixing," in EnglishColour Vision Deficiencies XII, ser. Documenta Ophthalmologica Proceedings Series, B. Drum, A. Adams, C. Cavonius, S. Dain, G. Haegerstrom-Portnoy, K. Kitahara, K. Knoblauch, A. Kurtenbach, B. Lee, J. Mollon, J. Moreland, J. Pokorny, L. Sharpe, H. Sperling, W. Swanson, and E. Zrenner, Eds. Springer Netherlands, 1995, vol. 57, pp. 193–196.

[8] Y. Zhao, Z. Chen, C. Zhu, Y.-P. Tan, and L. Yu, "Binocular just-noticeable-difference model for stereoscopic images," Signal Processing Letters, IEEE, vol. 18, no. 1, pp. 19–22, Jan 2011.

[9] F.L. Kooi and A. Toet, "Visual comfort of binocular and 3D displays," Displays, vol. 25, no. 2-3, pp. 99–108, Aug. 2004.

[10] Frank L. Kooi and Alexander Toet, “Visual comfort of binocular and 3d displays,” Displays, vol. 25, no. 2–3, pp. 99 – 108, 2004.

[11] R.T.H. Kane, David and M. S. Banks, “Visual discomfort with stereo 3d displays when the head is not upright,” Proceedings of SPIE, 2012.

[12] Y.H. Lin and J.L. Wu, “Binocular perceptual model for symmetric and asymmetric 3d stereoscopic image compression,” in Data Compression Conference (DCC), 2014, March 2014, pp. 113–122.

[13] S. Pastoor, “Human factors of 3d imaging: Results of recent research at heinrich-hertz-institut berlin,” Proceedings of the International Display Workshop ’95, vol. 3, p. 66–72, 1995.

[14] D. Kim, S. Choi, and K. Sohn, Circuits and Systems for Video Technology, IEEE Transactions on, no. 5, pp. 811–816, May.

[15] M. Lambooij, H. Marc; Fortuin, “Visual discomfort and visual fatigue of stereoscopic displays: A review,” Journal of Imaging Science and Technology, vol. 53, pp. 30201–1–30201–14(14), May 2009.

[16] S. Yano, M. Emoto, and T. Mitsuhashi, “Two factors in visual fatigue caused by stereoscopic {HDTV} images,” Displays, vol. 25(4), pp. 141 – 150, 2004.

[17] Y.J. Jung, D. Kim, H. Sohn, S.-i. Lee, H. W. Park, and Y.M. Ro, “Subjective and objective measurements of visual fatigue induced by excessive disparities in stereoscopic images,” pp. 86480M–8, 2013.

[18] M. Park and S. Mun, “Overview of measurement methods for factors affecting the human visual system in 3d displays,” Display Technology, Journal of, vol. PP, no. 99, pp. 1–1, 2015.

[19] R. Pascaline Neveu, Matthieu Philippe, “Vergence tracking: a tool to assess oculomotor performance in stereoscopic displays,” Journal of Eye Movement Research, vol. 5(2):1, pp. 1–8, 2012.

[20] H.D.B.M. Shibata T, Kim J, “Visual discomfort with stereo displays: Effects of viewing distance and direction of vergence-accommodation conflict,” Proceedings of SPIE, 2011.

[21] K. Ukai and P. A. Howarth, “Visual fatigue caused by viewing stereoscopic motion images: Background, theories, and observations,” Displays, vol. 29, no. 2, pp. 106 – 116, 2008, health and Safety Aspects of Visual Displays.

[22] A.T. Duchowski, B. Pelfrey, D.H. House, and R. Wang, “Measuring gaze depth with an eye tracker during stereoscopic display”, 15–22, 2011.

[23] E.C. Lee, H. Heo, and K. R. Park, “The comparative measurements of eyestrain caused by 2d and 3d displays,” Consumer Electronics, IEEE Transactions on, vol. 56, no. 3, pp. 1677–1683, Aug 2010.

[24] D.K. Kim, Joohwan and M. S. Banks, “Visual discomfort and the temporal properties of the vergence-accommodation conflict,” Proceedings of SPIE, 2012.

[25] B. David M. Hoffman, Ahna R. Girshick, “Vergence–accommodation conflicts hinder visual performance and cause visual fatigue,” Journal of Vision, vol. 8, pp. 1–30, 2008.

[26] S.O. Lina Jansen and P. König, “Influence of disparity on fixation and saccades in free viewing of natural scenes,” J. of Vision, vol. 9, 2009.

[27] P. Wolffsohn, James Stuart Phd, “Dynamic measurement of accommodation and pupil size using the portable grand seiko fr-5000 autorefractor,” Optometry & Vision Sc., vol. 83, pp. 306–310, 2006.

[28] J.S. Wolffsohn, O. A. Hunt, and B. Gilmartin, “Continuous measurement of accommodation in human factor applications,” Ophthalmic and Physiological Optics, vol. 22, no. 5, pp. 380–384, 2002.

[29] H.-C. Li, J. Seo, K. Kham, and S. Lee, “Measurement of 3d visual fatigue using event-related potential (erp): 3d odd ball paradigm,” in 3DTV Conference: The True Vision - Capture, Transmission and Display of 3D Video, 2008, May 2008, pp. 213–216.

[30] Y. Bi and J. Zhou, “A visual comfort metric for stereoscopic 3d video based on smde approach,” in Signal Processing, Communication and Computing (ICSPCC), 2012 IEEE Int. Conf. on, Aug 2012, pp. 72–77.

[31] V. Kulyk, S. Tavakoli, M. Folkesson, K. Brunnstrom, K. Wang, and N. Garcia, “3d video quality assessment with multi-scale subjective method,” in Quality of Multimedia Experience (QoMEX), 2013 Fifth International Workshop on, July 2013, pp. 106–111.

[32] V. De Silva, H. Arachchi, E. Ekmekcioglu, and A. Kondoz, “Toward an impairment metric for stereoscopic video: A full-reference video quality metric to assess compressed stereoscopic video,” Image Processing, IEEE Transactions on, vol. 22, no. 9, pp. 3392–3404, Sept 2013.

[33] F.L.M.Y. Shanshan Wang, Feng Shao and G. Jiang, “A simple quality assessment index for stereoscopic images based on 3d gradient magnitude,” The ScientificWorld Journal, vol. Volume 2014, Article ID 890562, 2014.

[34] A. Liu, W. Lin, and M. Narwaria, “Image quality assessment based on gradient similarity,” Image Processing, IEEE Transactions on, vol. 21, no. 4, pp. 1500–1512, April 2012.

[35] P.C.R.C. Alexandre Benoit, Patrick Le Callet, “Quality assessment of stereoscopic images,” EURASIP Journal on Image and Video Processing, vol. 2008 (1), 2008.

[36] C. Hewage, S. Worrall, S. Dogan, S. Villette, and A. Kondoz, “Quality evaluation of color plus depth map-based stereoscopic video,” Selected Topics in Signal Processing, IEEE Journal of, vol. 3, no. 2, pp. 304–318, April 2009.

[37] W.F.P. Joveluro, H. Malekmohamadi and A. Kondoz, “Perceptual video quality metric for 3d video quality assessment,” In 3DTV-Conference: The True Vision - Capture, Transmission and Display of 3D Video, pp. 1–4, 2010.

[38] L. Xing, “Towards reliable stereoscopic 3d quality evaluation, subjective assessment and objective metrics,” Ph.D. dissertation, Norwegian University of Science and Technology, Faculty of Information Technology, 2013.

[39] D. Juszka, L. Janowski, and Z. Papir, “Objective bitstream quality metric for 3d-hd video,” in 3D Imaging (IC3D), 2013 International Conference on, Dec 2013, pp. 1–5.

[40] S. Ryu, D. H. Kim, and K. Sohn, “Stereoscopic image quality metric based on binocular perception model,” in Image Processing (ICIP), 2012 19th IEEE International Conference on, Sept 2012, pp. 609–612.

[41] J. Yang, C. Hou, R. Xu, and J. Lei, “New metric for stereo image quality assessment based on hvs,” International Journal of Imaging Systems and Technology, vol. 20, no. 4, pp. 301–307, 2010

[42] F. Timm and E. Barth, “Accurate eye centre localisation by means of gradients,” SciTePress, pp. 125–130, 2011.

[43] Marcus Barkowsky, Romain Cousseau, Patrick Le Callet. Is visual fatigue changing the perceived depth accuracy on an autostereoscopic display?. Stereoscopic Displays and Applications XXII, Jan 2011

[44] W.J. Tam, F. Speranza, S. Yano, K. Shimono, and H. Ono, “Stereoscopic 3d-tv: Visual comfort,” Broad-casting, IEEE Transactions on, , no. 99, pp. 1–1, 2011.

[45] H. Pan, C. Yuan, and S. Daly, “3d video disparity scaling for preference and prevention of discomfort,” Stereoscopic Displays and Applications XXII, SPIE Vol, vol. 7863, 2011

[46] C. Yuan, H. Pan, and S. Daly, “61.3: Stereoscopic 3d content depth tuning guided by human visual models,” SID, 2011.

[47] Stephan Reichelt, Ralf Häussler, Gerald Fütterer, and Norbert Leister, "Depth cues in human visual perception and their realization in 3D displays“, Three-Dimensional Imaging, Visualization and Displays 2010

[48] Jae Gon Kim, Nonmember and Jun-Dong Cho “Simplified Relative Model to Measure Visual Fatigue in a Stereoscopy” IEICE TRANS. FUNDAMENTALS/COMMUN./ELECTRON./INF. 2015

[49] Song-Pei Du, Belen Masia, Shi-Min Hu, and Diego Gutierrez. 2013. A metric of visual comfort for stereoscopic motion. ACM Trans. Graph. 32, 6, Article 222 (November 2013)

[50] D. Puchala, B. Stasiak, K. Stokfiszewski and M. Yatsymirskyy, „Image Filtering with Fast Parametrized Biorthogonal Transforms Implemented on a New GUI Research Aid System”, JACS vol. 21(2), pp. 97-115, 2013

[51] J. Li, M. Barkowsky, P. Le Callet, „Visual Discomfort Is Not Always Proportional To Eye Blinking Rate: Exploring Some Effects Of Planar And In-Depth Motion On 3dtv Qoe”, Int. Workshop on Video Processing and Quality Metrics for Consumer Electronics VPQM, pp. 1-6, 2013

[52] D. Vatolin, A. Voronov, D. Sumin, G. Rozhkova, et. al., Stereo film quality analisis, VQMT3D project raport, CS MSU Graphics and Media Lab, 2013

Krzysztof Fornalczyk graduated Computer Science and Information Technology at Lodz University of Technology, Poland in 2015. Currently he continues education as a PhD student at the Lodz University of Technology at Faculty of Technical Physics, Information Technology and Applied Mathematics. His bachelor and master thesis as well as scientific interests include eye-tracking systems and image processing.

Piotr Napieralski received the MSc degree in Information Technology from the Lodz University of Technology, Poland in 2000, and the Ph.D. degree in Information Technology from the Silesian University of Technology, Poland in 2008. In 2014 he received the DSc (habilitation) in Information Technology from , Lodz University of Technology, Poland. Currently, he is an Associate Professor in Institute of Information Technology, Lodz University of Technology, Poland. He has published 30 technical papers. His research interests include methods of real time rendering, algorithms and methods for global illumination, stereoscopic images and mobile systems design.

Dominik Szajerman was born in Lodz, Poland, in 1977. He graduated in computer graphics and obtained the Ph.D. degree from Department of Technical Physics, Information Technology and Applied Mathematics at Technical University of Lodz, Poland, in 2001 and 2010, respectively. During his pre- and postgraduate experience he was involved in a number of research projects in the areas of computer graphics, computer games and human-computer interaction. His academic interests lie in the computer graphics, GPU processing, computer games development and image processing.

Adam Wojciechowski was born in Lodz, Poland in 1974. He graduated in 1999 at the Lodz University of Technology, Poland, where he received MSc in Computer Graphics and Multimedia. He obtained PhD degree from the Faculty of Automatics, Electronics and Computer Science, Silesian University of Technology, Poland in 2005. In 2014 he received the DSc (habilitation) from the Faculty of Mechanical Engineering and Computer Science, Czestochowa University of Technology. His current research interests include such disciplines as human-machine interaction, virtual environments, image processing, computer games and computer graphics.