Visual Discomfort in Stereoscopic Displays: A Review

Marc T.M. Lambooij[a,b], Wijnand A. IJsselsteijn[a], Ingrid Heynderickx[b]

[a] Human-Technology Interaction Group, Department of Technology Management, Eindhoven University of Technology, Eindhoven, The Netherlands
[b]Group Visual Experiences, Philips Research Laboratories, Eindhoven and
Department Mediamatics, Delft University of Technology, Delft, The Netherlands

Abstract

Visual discomfort has been the subject of considerable research in relation to stereoscopic and autostereoscopic displays, but remains an ambiguous concept used to denote a variety of subjective symptoms potentially related to different underlying processes. In this paper we clarify the importance of various causes and aspects of visual comfort. Classical causative factors such as excessive binocular parallax and accommodation-convergence conflict appear to be of minor importance when disparity values do not surpass one degree limit of visual angle, which still provides sufficient range to allow for satisfactory depth perception in consumer applications, such as stereoscopic television. Visual discomfort, however, may still occur within this limit and we believe the following factors to be the most pertinent in contributing to this: (1) excessive demand of accommodation-convergence linkage, e.g., by fast motion in depth, viewed at short distances, (2) 3D artefacts resulting from insufficient depth information in the incoming data signal yielding spatial and temporal inconsistencies, and (3) unnatural amounts of blur. In order to adequately characterize and understand visual discomfort, multiple types of measurements, both objective and subjective, are needed.

Keywords: visual comfort, visual fatigue, human factors, stereoscopic displays, review

1. INTRODUCTION

> *"Stereoscopic viewing was indeed fashionable. As if by magic the world was available for all to see,*
> *as entertainment, as education, in startling realism in the comfort of the home."*
> Portrayal of the enthusiasm around 1855's[1]

The introduction of three dimensional television (3D TV) on the public consumer market, much like its desktop-counterpart in the gaming and internet industry, is believed to be just a matter of time and has been compared to the transition from black-and-white to color TV. Others state that it brings the viewer a whole new experience, "a fundamental change in the character of the image, not just an enhancement of the quality"[2]. To be a success, both image quality and visual comfort must at least be comparable to conventional standards to guarantee a strain free viewing experience[3]. Since this promise has not yet been accomplished, extensive research to understand the factors underlying viewing discomfort is needed. An overview of the current status of that research is described in this paper. Classic works in this area mention conflicts between accommodation and convergence, excessive binocular parallax and dichoptic errors as major problems to visual comfort. These factors will be reviewed in this paper as well as some additional causes that might have become more relevant nowadays with the evolution in 3D systems. We also emphasize some experimental settings necessary to qualify or quantify the degree of visual comfort in an unambiguous manner.

2. HUMAN PERCEPTION OF DEPTH

> *"A painting, though conducted with the greatest art, and finished to the last perfection,*
> *both with regard to its contours, its lights, its shadows, and its colors,*
> *can never show a relief equal to that of the natural objects*
> *unless these be viewed at a distance and with a single eye."*
> Leonardo da Vinci (1584) in Wheatstone (1828)[4]

Humans perceive depth, which is remarkable, because the retinal images, from which depth information is extracted, are strictly two-dimensional. However, even two-dimensional natural scenes contain a great amount and diversity of visual

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cues for the perception of depth. These are so-called monocular cues. Our visual system utilizes these cues and constructs a 3D representation of the perceived scene. A detailed review of monocular depth cues is beyond the scope of this review, but can be found in Sekuler & Blake (2002)[5]**.** Apart from monocular cues, more specific depth information can be obtained from binocular cues, especially at shorter viewing distances. These cues are implemented in (auto)stereoscopic displays. Based on these cues, viewers may achieve a more natural depth perception, but sometimes at the expense of visual comfort. In this review only those cues that bear relevance to visual discomfort induced by (auto)stereoscopic displays, will be described.

2.1. Binocular depth perception

Because our eyes are horizontally separated, each eye has its own viewpoint of the world and thus both eyes receive slightly different retinal images. Stereopsis is the perception of depth that is constructed based on the difference between these two retinal images; the brain fuses the left and right image and from retinal disparity, i.e., the distance between corresponding points in these images, the brain is able to extract depth information.

Points that are fixated on fall on corresponding parts of the retina, and thus have zero retinal disparity. For any degree of convergence, the horopter is the line that connects all points in space that stimulate corresponding retinal points, i.e., that all have zero retinal disparity[2]. Points that do not fall on the horopter have retinal disparity. Objects located in front of the horopter will have crossed disparity and objects located behind the horopter will have uncrossed disparity. A small region around the horopter, called Panum's fusional area, is the region where binocular single vision takes place, i.e., where the two retinal images are fused into a single image in depth.

The limits of Panum's fusional area are not constant over the retina, but expand at increasing eccentricity from the fovea. At the fovea the limit of fusion is equal to a maximum disparity of only one-tenth of a degree, whereas at an eccentricity of 6º, the maximum disparity is limited to one-third of a degree[6-8] and at 12º degrees of eccentricity without eye movements the maximum value is approximately two-third of a degree[7].

2.2. Accommodation, vergence and depth of field

Whenever we look at objects, our eyes are accommodated and converged by an amount that depends on the distance between us and the object of interest. Vergence can be defined as movement of the two eyes in opposite direction to locate the area of interest on the fovea, a process that is primarily disparity driven. Accommodation can be defined as alteration of the lens to focus the area of interest on the fovea, a process that is primarily driven by blur[9,10].

Under natural conditions the accommodation and vergence systems are intrinsically and reflexively linked[11-14]. The amount of accommodation required to focus on an object, changes proportionally with the amount of vergence needed to fixate that same object in the center of the eyes. Under conditions of binocular fusion, for a certain amount of vergence, accommodation has a certain range, or depth of focus, in which it can move freely and objects are perceived properly[15-18]. Similarly, the vergence system has an analogous range as well. The ranges of accommodation and vergence where both systems do not introduce any errors, form "the zone of clear, comfortable, binocular vision"[15].

Each single eye has a depth of focus so it does not depend on stereoscopic vision; it simply defines the zone where vision is sharpest. For a certain amount of vergence and accommodation there is a small range of distances at which an object is perfectly focused; deviations in either direction gradually introduce blur.

The abbreviation of depth of focus, DOF, is also used to abbreviate depth of field and both terms are used interchangeably. Depth of field represents the range of distances for which an object is in focus for a given state of accommodation[8]. If depth of focus describes acceptable ranges of focus around the retina, depth of field describes acceptable ranges of focus in front of the eye and expressed in vergences, both fields are equal[19]. In the remainder of this paper, DOF refers to depth of field.

2.3. Depth cue integration

As mentioned before, the brain combines depth information from multiple cues, both monocular as well as binocular. In the perception of objects in our everyday environment, combinations of different depth cues normally reduce ambiguity and contribute to a consistent perception of depth. In stereoscopic display situations, however, cues may conflict. It remains an ongoing debate which strategy the brain uses to extract depth[20] and a single unified theory about cue integration is not established yet[6], though recent research seems to show consensus on depth cue integration in terms of statistical inference[21]. The interesting question is not how depth perception is affected when different depth cues are combined, but when cues conflict. Cutting & Vishton (1995) provide an overview of the relative importance of different depth cues at various distances[22]. They illustrate among others that occlusion is dominant over all other cues, and is only approached by binocular disparity, as well as the small effect of accommodation and convergence.

2.4. Individual differences

People not only personally differ in their preference for stereoscopic applications, but also their gender, race and age might affect their preference for stereoscopy, since these sources of individual variations are known to affect some human visual system characteristics that directly determine stereopsis. For example, an important characteristic that differs between individuals is the interpupillary distance (IPD). Both angular disparity and perceived depth depend on the IPD. Extensive research on the IPD of humans of different gender, race and age showed that the IPD of the vast majority of adults falls within the range of 50 to 70 mm, with a mean and median of approximately 63 mm, though to include extremes and children a range of 40 to 80 mm is necessary[23]. People with a smaller IPD perceive more depth than people with a large IPD for a fixed screen disparity and viewing distance, so they reach disparity limits more rapidly. The AC/A ratio is another characteristic that differs between individuals. It describes the change in convergence due to accommodation per change in accommodation, i.e., the magnitude of the crosslink-interaction. It seems that people with extremely high AC/A ratios have trouble with binocular fusion and depth perception[24]. Finally, differences in pupil diameter between individuals also affect stereoscopy. Generally, pupil diameter depends on light level, age, gender and mental activity[5]. A decrease in luminance enlarges the pupil diameter, and as such decreases the quality of the image due to a diffraction decrease and a spherical aberration increase and reduces the DOF as well[8].

Visual abilities also vary with age as a result of changes in the structures of the eye. Accommodative ability decreases with age, starting around 40 years up to approximately 55 years, when little or no accommodation remains[25]. Conversely, the visual system of children still has a high degree of plasticity, because it is not fully developed until the age of seven[13]. This is the main reason why some researchers advise against stereoscopic viewing for children, stating that even though little evidence exist that viewing stereoscopic content causes permanent damage to the vision system, there is also no evidence that contradicts this argument". For some research this is cause for careful study for their undeveloped visual system as longterm effects of viewing stereoscopic content are yet unknown.

3. VISUAL COMFORT

> *"Palsy and insanity are not infrequent consequences of masturbation.*
> *I have often ascertained that asthenopia, in young men, is a result of excessive veneral indulgence,*
> *but frequently still, of masturbation, or of involuntary emissions.*
> *I have no doubt that masturbation is a frequent cause of the same complaint in females."*
> MacKenzie (1843)[26] in Ebenholtz (2001)[17]

Over the last decades, safety and health issues related to video display terminals (VDTs) in general, and stereoscopic displays specifically, have been extensively studied. Especially for 3D TV, literature describes visual discomfort as the number one health issue. Hence, for the development of a strain free viewing experience on a stereoscopic display, an all-inclusive study of visual comfort is required.

In literature, visual comfort is used interchangeably with visual fatigue. A distinction, however, should be made, since visual fatigue refers to a decrease in performance of the human vision system, which can be objectively measured, whereas visual comfort is its subjective counterpart. This relationship is generally assumed, but to our knowledge never carefully verified. In this review the distinction between visual fatigue and visual comfort will be consistently used. When formulated in this way, perceived visual comfort determined via subjective measurements, is expected to provide an indication of the objectively measurable visual fatigue.

The diagnostic term for visual fatigue is asthenopia and literally means "eye without strength"[26]. Asthentopic pain may be concentrated around the eyes, or may be diffuse as a general headache or occur in the neck and shoulders. Much research has been conducted in the past concerning visual fatigue, though its conceptualization remains ambiguous: across different fields, different definitions are used, but no absolute definition exist[27,28]. In most cases visual fatigue is defined as a combination of underlying causative factors and symptoms.

The causes of visual fatigue are very diverse, and therefore, are still a source of ongoing research. Especially in the area of VDT visual fatigue can be caused or induced by anomalies of vision such as esophoria and convergence insufficiency, accommodative dysfunctions, uncorrected refractive error including presbiopia, and by display issues such as compromised quality of the viewed image, flickering stimuli, suboptimal gaze angles, viewing distance and display technology[28-31]. Research concentrated on stereoscopic displays revealed that causes of visual fatigue include (1) anomalies of binocular vision, (2) dichoptic errors, like geometrical distortions between left and right images such as keystone distortion, depth-plane curvature, crosstalk and binocular rivalry, (3) conflict between convergence eye movement and accommodation functions and (4) excessive binocular parallax[18,32-35].

Directly related to the extensive list of causative factors is the amount and diversity of symptoms of visual fatigue. To give a clear overview, the various symptoms [29,30,32,36-38] are grouped according to a specific categorization[31]. The first group is *asthenopic* with eyestrain, tired and sore eyes, feeling of pressure in the eyes and chemical changes in intracorporeal substances. The second group is *ocular surface-related* including dried mucus, painful irritation, lachrymation, reddening of the eyes and conjunctivas. The third group is *visual* including double vision, blurred vision, slowness of focus change, reduced sensitivity to spatial contrast, visual acuity and speed of perception, reduced power of accommodation and convergence and presbiopia. And the fourth group is *extra ocular* and includes headaches, ache around the eyes, neck pain, back pain and shoulder pain, distortions of psychological activities in humans and subjective symptoms such as a decline in work efficiency and loss of concentration.

As a consequence of the multiple causative factors and symptoms, the indicators for measuring visual fatigue and visual comfort are also numerous and widespread[28,32,36]. Possible objective indicators for measurement of visual fatigue are pupillary diameter, near and light pupillary reactions, critical fusion frequency, visual acuity, near point, refractionability, visual field, stereo acuity, fixation stability, accommodative response, AC/A ratio, heterophoria, convergent eye movement, spatial contrast sensitivity, color vision, light sense, blink rate, tear film breaking time, pulse rate and respiration time. Subjective indicators for measurement of visual comfort include subjective self-assessments such as assessment scales and questionnaires, though to our knowledge a generally accepted questionnaire that proved to be sensitive, valid, reliable and robust, has not yet been established. Pupillary diameter is stated to be suitable for the assessment of visual fatigue, as it is correlated with pupillary responses that reflect the activity of the autonomic nervous system and thus the accommodative functions[36,37].

An essential issue in determination of visual fatigue is the presence of simultaneous symptoms. A single causative factor, e.g., conflict in vergence eye movement, can stimulate different anatomical locations, which most likely results in different sensations[30]. Hence, the concept visual fatigue cannot be evaluated with only one indicator[36,37]. In addition, many of the ocular changes representing visual fatigue, can also be regarded as a healthy characteristic of our biological system adapting to altered visual environments. Only physiological changes that are accompanied by negative psychological effects in function or comfort are of interest here and should be critically examined for their magnitude and subjective impact. This inherently subjective character of visual fatigue, i.e., visual comfort, and its dependence on individuals' self-appraisal must be evaluated on a perceptual basis via subjective assessment methods and questionnaires[3,29,33,39,40]. Multiple types of measurements, both objective as well as subjective, need to be combined in order to determine the degree of visual fatigue and visual comfort in a sensitive, accurate, reliable and valid way. An all inclusive definition may be impossible, however, due to the spider web of relations between causative factors, symptoms and indicators, accurate research-specific operationalizations of visual comfort and visual fatigue will also be highly valuable.

4. CAUSATIVE FACTORS: AN EMPIRICAL DESCRIPTION

The Miracle of the Age!!! A LION in your lap! A LOVER in your arms!
Tagline of Bwana Devil, the first feature length 3D cinema movie (A. Oboler, 1952)

From 1952 to 1954, stereoscopic films were at the height of their popularity, with Hollywood producing more than 65 stereoscopic feature films. However, viewers' interest rapidly declined after this initial success. Reasons for this are varied including increased competition from other immersive cinema formats. Undeniably, however, some of the problems with 3D cinema appear to be associated with issues of visual discomfort, produced by crosstalk through suboptimal (but cheap) image separation techniques, the use of excessive disparities and in-your-face stereoscopic content, and misalignment of projectors in the cinema[2]. In the next section we will describe factors that are thought to cause visual discomfort in stereoscopic displays.

4.1. Excessive binocular disparity

As discussed previously, fusion limits can be remarkable small. Without vergence movements and for brief stimulus duration, values as small as 27 min of arc for crossed and 24 min of arc for uncrossed disparity are found, though with longer stimulus durations and convergence eye movements, disparities as large as 4.93 degrees for crossed and 1.57 degrees for uncrossed disparity can be fused without diplopia[41]. This spread in limits of disparity raise questions concerning the classical notation of Panum's fusional area as being an absolute limit for disparities that can be fused[42]. Many factors affect the limits of Panum's fusional area, including stimulus size, spatial frequency, temporal modulation of disparity information, exposure duration, continuous features, temporal effects, amount of luminance and individual differences[6,7,42-44]. The limits increase with larger, moving objects and decrease with smaller, detailed and stationary objects[6]. The addition of peripheral objects to the fixation object, improves fusion[45] and fusion limits can be modified by training[46]

4.2. Accommodation and convergence mismatch

The distance towards objects in the real world is estimated by our visual system from among others the linkage between accommodation and vergence. (Auto)stereoscopic displays in contrast, generate an artificial environment, where the intrinsic coupling between accommodation and vergence is lost. As distance between virtual object and display increases, light emitted by the display becomes more diffuse and the object is perceived as more blurred. While our eyes fixate (converge) on the virtual 3D-object, the display requires the eyes to focus (accommodate) on the screen where the image is displayed sharpest. Hence, accommodation distance is constant, but vergence distance varies depending on degree and sign of disparity. As a consequence, distance of focus is independent of distance of fixation.

In the literature it is argued that this process of decoupling the linkage between accommodation and convergence, induces visual fatigue[18,47-54]. Though many researchers argue that this decoupling may potentially be the primary cause of visual fatigue, research reveals contradictionary results[55,56]. These findings raise the questions whether a conflict between accommodation and convergence occurs at all, and how it is related to the depth of focus of the eye[15]. For a certain amount of disparity, accommodation is able to focus the object sharply on the retina, as long as the distance from the reconstituted object to the display remains within the range of DOF[57]. Once the reconstituted object has too much disparity, i.e., the stereoscopic depth is larger than the DOF, the accommodation response is suppressed independent of the amount of vergence[58]. Once our visual system moves beyond this zone, three errors can occur: loss of fusion, where accommodation remains and double vision occurs, loss of accommodation resulting in a blurred image, or both. In these situations it is the effort of the oculomotor system for correction of the situation that directly causes the fatigue, not the artefact.

The range of DOF is influenced by many factors, some of which are related to target attributes, e.g., contrast and spatial frequency, and some to eye/brain attributes, e.g., pupil size and age[59,60]. Depth of focus ranges from ± 0.02 to ± 1.75 diopter[59], though some clinical research has reported values that even surpass two diopter[61].

4.3. Panum's fusional are and DOF revisited

Under natural viewing conditions, range of depth of focus concurs with range of fusion[16,58,62]. Objects at increasing distance from the fixation point, are perceived as more blurred. As a consequence, diplopia is postponed, because limits of Panum's fusion area are increased as result of the decreased spatial frequency. In principle, if both visual systems complement each other in this manner, it is expected that their limits should match.

An accepted limit for DOF in optical power for a 3 mm pupil diameter (common under normal daylight conditions) and the eyes focusing at infinity, is one-third of a diopter[6]. With respect to the revisited Panum's fusion area, disparities beyond one degree (a conservative application of the 60 to 70 arcmin recommendation[34,63]), are assumed to cause visual discomfort, which actually results from the human eye's aperture and depth of focus[63]. Though this nowadays serves as a rule-of-thumb, it is acknowledged as a limit, cause lower recommendations have been reported as well[35,64]. If both the limits of disparity and DOF are calculated in distances, they show very high resemblance. Hence, a general limit can be applied, excluding the extensive list of factors that underlie both concepts. Table 1 depicts this general limit of one degree of disparity for comfortable viewing for different viewing distances in terms of distances.

Table 1 **Limits for comfortable viewing at different viewing distances**

	Limits for comfortable viewing	
View. dist. (mm)	near (mm)	far (mm)
500	440	580
1000	780	1400
2000	1300	4500
3000	1600	17000

Hence, to accept this limit of one degree of disparity as a applicable boundary for comfortable viewing, it is necessary to demonstrate and verify that stereoscopic image content beyond the limit results in visual discomfort in contrast to within this limit. It is expected that beyond the one degree limit, there is a zone of increasing visual discomfort up to a value where diplopia appears. Because diplopia occurs at much higher disparity values[7], most research concerning this limit concentrated on measurements on the oculomotor system instead of on fusion limits.

4.3.1. Beyond the zone of comfortable viewing

Yano et al. [18] performed an experiment where they evaluated the range of disparity and comfortable viewing for still images, both subjectively, using a self-assessment test, and objectively, with pre- and post accommodation responses. The subjective evaluation revealed higher values for visual discomfort when images were displayed beyond the limit of comfortable viewing, which was confirmed by their objective measurements. Plausibly due to the small number of participants (N=6), the average decrease in visual comfort was significant for uncrossed disparity, but not for crossed disparity. For evaluation of the effect of vergence load on Percival's area of comfort[32], an area almost similar to the range of DOF in terms of being limited on both sides of the display[18], both subjective and objective measurements were used for stereoscopic sequences. The subjective evaluation indicated a higher degree of discomfort with heavy or temporally changing vergence loads, which was confirmed by the objective measurements of vergence responses, but not by accommodation responses. It was apparent, though not conclusive, that next to excessive disparity, temporal changes in disparity is a major factor of visual fatigue, possibly caused by the dissociation of accommodation and convergence.

In another study, Okada and colleagues[53] applied different degrees of blur (i.e. accommodation) to still images at different degrees of disparity exceeding the limit of comfortable viewing. Both accommodation and convergence responses were measured and revealed that without disparity, accommodation responses were relatively constant independent of degree of blur, but with large disparity, accommodation shifted towards the target under the influence of convergence-driven accommodation. This shift increased systematically with increased degrees of blur, indicating a dissociation between accommodation and convergence that affected accommodation for disparities beyond the DOF. The effect of this dissociation on visual comfort could not be verified, since no subjective evaluations were incorporated.

4.3.2. Within the zone of comfortable viewing

Within the zone of comfortable viewing, visual discomfort should not occur. However, for sequences, visual comfort decreased as a consequence of high disparity or much variation in disparity[65]. Other research found contradictionary results in measurements of accommodation responses for stereoscopic sequences[66]. Differences in pre- and post accommodation response as an indication for visual fatigue were occasionally found, but not confirmed in the subjective evaluation. Using the continuous subjective assessment methodology, however, revealed that visual discomfort was related to image content: visual comfort received local low evaluation scores for scenes with high degrees of disparity and high amounts of motion. Additional research confirmed that the introduction of depth motion in stereoscopic sequences resulted in a decrease of accommodation response and a significant decrease of visual comfort[18]. To further clarify the influence of changing disparity magnitudes in time, a relationship between amount of disparity, object motion and visual comfort must be verified[34]. For different degrees of disparity, periodically changing disparity from crossed to uncrossed as well as the rate of this change in disparity influence visual comfort to a larger extent than the amount of disparity, which in some conditions even surpassed one degree of disparity.

It seems that visual discomfort increases when the demand on the oculomotor system increases as well, as is the case with motion in depth and spatial direction, and for disparities approaching the one degree limit. It is expected that prolonged viewing and short viewing distances result in an further increase in demand, and thus in a further increase of visual discomfort. More detailed research is needed to further clarify the relationship between accommodation and convergence with dynamic stereoscopic sequences within the DOF.

4.4. Stereoscopic distortions

Stereoscopic distortions result from several stages in the generation process of 3D content, namely content generation (choice of camera, camera configuration, 2D-to-3D conversion), coding and transmission (compression), rendering (multiple views rendered from a single view) and type of display. Literature describes several types of distortions that can induce visual discomfort and can occur simultaneously[35]. Generation related distortions include keystone distortion, depth-plane curvature, puppet theatre effect, cardboard effect, shear distortion, and display related distortions include picket fence effect, image flipping and crosstalk. We will not discuss them in detail here, as their technological causes and perceptual effects are well-understood. Recent detailed descriptions of these geometrical stereoscopic distortions, are provided by Meesters et al.[3] and IJsselsteijn et al.[33].

Crosstalk is an artefact that results from imperfect separation of the left and right eye's view. It is often used interchangeably with ghosting, though a distinction should be made. "Crosstalk is electrical or optical mixing of left- and right-eye images"[67]. It may result in perceived ghosting, but also in blurring. Research mentioned crosstalk as one of the main display-related perceptual factors degrading image quality and visual comfort[33,40].

In some cases, however, crosstalk may also have some beneficial effects on image quality and visual comfort. Autostereoscopic multi-view displays intentionally induce a certain amount of crosstalk to avoid a picket-fence effect (banding) and to minimize image flipping (the discrete transitions between neighboring views). Small disparities limited to the fore- and background regions combined with crosstalk (up to 40%, i.e., 20% of each of the neighboring views) are perceived as blur instead of ghosting[67]. Nonetheless, perception of depth is preserved. The optimal amount of crosstalk is still an issue of debate; the amount of induced depth should be a balance between annoying degrees of blur, perceived banding and clear transitions between views.

4.4.1. An artificial DOF

In real world situations, objects that appear at large distances both in front and behind the fixation point, are blurred and do not stimulate fusion. In most stereoscopic scenes, however, the entire stereoscopic image is displayed sharply, because different viewers may concentrate on different parts of the image. Sharply displayed objects with a disparity beyond the fusion limit, still elicit on effort to fuse in both eyes yet fusion is not possible due to the large disparity[68]. The lack of blur in these stereoscopic displays can reduce range of fusion. Because limits of fusion increase with decreasing spatial frequency, artificially blurring images to a degree that corresponds to the amount of depth, may increase the range of fusion and even visual comfort. Objects fixated on must be displayed in full resolution, whereas other regions must have a depth-dependent blurriness, which could result in fusion of excessive parallax. Three essential steps must be implemented to simulate such a DOF: localization of the eye positions[68], determination of the fixation point[67] and implementation of blurring filters to non-fixated layers[69]. Hence, this solution for increased visual comfort might have practical limitations with some 3D-display technology, e.g., in the case of multiple viewers.

Other research applied a different approach[64,70]. To avoid blurring of extensive depth ranges it is possible to map the scene depth range on the perceived depth range, though this might result in compression artefacts and unnatural depth perception. A new approach was introduced that compressed only the most outer regions, i.e., not the region of interest[70]. The solution has been implemented, but not yet evaluated on a perceptual base.

4.4.2. 3D artefacts

To guarantee large amounts of 3D content for (auto)stereoscopic displays, (real-time) 2D-to-3D conversion is a promising method, especially with digital television content, since research has demonstrated that generated depth only has to approach reality to create an acceptable 3D percept[3]. Hence, development of these conversion algorithms is based on the assumption that geometrically accurate depth is not necessary; a good depth impression on screen will suffice. This quasi depth ordering process relies on assumptions, estimations and heuristic cues[71-73] and can result in artefacts. These artefacts include spatial and temporal inconsistencies, e.g., objects or parts of objects that are assigned incorrect depth values and therefore allocated to incorrect depth layers. This may lead to incorrect blurring and pixel rendering, and unnatural visualizations, e.g., flickering of (parts of) the image and turbulence around the edges.

Unnatural visualizations may also result from disocclusion, i.e., image content unavailable from the original 2D image source because of occlusion, suddenly becoming visible in any of the virtual views[74]. Since no information of the occluded objects is available from the original image content, the missing areas (often referred to as *holes*), must be replaced with 'useful' color information. Different algorithms are available for this hole-filling procedure[74-87]. All these techniques, however, experience the same shortcoming, namely that the occluded area is not based on, but interpolated from existing information. Hence, the 2D-to-3D conversion cannot be fully accurate, and artifacts related specifically to the 2D-to-3D conversion process are likely to occur. However, little is known about the effect of these artefacts of the depth ordering processes on visual discomfort. Of course, misallocated objects could cause conflicts between binocular disparity and other depth cues and such conflicts are expected to be perceptually annoying, when the visual system cannot satisfactorily resolve them.

4.4.3. Blur

In real world situations, objects at different distances from the fixation point are blurred to extents proportional to this distance. As such, blur may facilitate depth perception, though in an ambiguous way for the following reasons: (1) polarity of the depth percept, i.e., objects both in front of and behind the fixation point can induce similar amounts of blur, and (2) because for a given convergence distance, the amount of blur depends, amongst others, on the DOF, a dynamic characteristic by itself[51]. Similar statements can be made for edges that are blurred, which serve as an effective, though ambiguous depth cue as well. As a consequence, increased amounts of blur resulted in more variation and in overestimation of depth[78].

Blur can occur as a 3D artefact that has different origins, i.e., crosstalk, 2D-to-3D conversion, rendering and artificially induced DOF. Consequently, it induces different perceptions: crosstalk results in blurred objects to an extent related to their amount of disparity; artificially induced DOF results in amounts of blur induced as a cue for distance perception; and conversion and rendering result in blur as a 3D artefact depending on image content and occurring more often at edges. Our visual system generally does not integrate blur and binocular disparity, since both cues are active over different ranges[79]. In stereoscopic displays, however, the visual system is often forced to do so, which could lead to unnatural or uncomfortable viewing situations. In conflicting situations with other depth cues, it is possible that blur serves as a final estimate, e.g., in case of misallocated objects, blur could favor incorrect depth perception and thereby increasing the conflict and eventually visual discomfort. Experiments indeed revealed that focus cues, both blur and accommodation, directly contribute to the overall 3D percept[51]. Even more, research has found that blur was one of the most important factors that determined viewing comfort[40].

5. DISCUSSION

Visual fatigue is related to many different aspects of the human visual system, thus remaining a somewhat ambiguous concept when used in a general sense. However for the purposes of our current review we define visual fatigue as physiological strain or stress resulting from exertion of the visual system. It is a state that can be objectively quantified in theory. However, in order to distinguish clinically significant visual fatigue from unproblematic, functional adaptations of the visual systems, we need to incorporate subjective indicators of visual discomfort. Appropriately developed and validated questionnaires or other self-report measures may provide such indicators, provided they are proven to be sensitive, reliable, valid and robust. Their subsequent application in evaluative settings is relatively easy. Visual fatigue, however, concerns measurements on the visual system that are generally costly, time-consuming and are usually conducted with only small amounts of subjects, making the measurements less reliable. Ideally, we would like to arrive at a general and easily applicable indicator of visual fatigue and visual discomfort. When a robust relationship has been established between visual discomfort and visual fatigue indicators, one might be used to substitute the other, where appropriate. Then, this would allow study of large groups of participants using easily applicable visual comfort measures. Moreover, it would apply to children as well, who may have some difficulties in filling in questionnaires. This latter group is of particular importance as they are expected to spend much time using 3D applications, yet whose developing visual systems have not been extensively studied in relation to their physiological responses to 3D television or gaming applications. Carefully conducted long-term evaluations will be necessary to ensure that prolonged stereoscopic viewing does not induce any adverse side-effects to the visual system.

With respect to the limit of disparity for comfortable viewing, the one degree of disparity appears to prevent the 'classical' causes of visual discomfort, i.e., excessive binocular disparity and accommodation-convergence conflict, from being perceptually annoying. Fusion is possible and blur is not perceived, hence, stereoscopic viewing should be comfortable within this limit. However, with certain stereoscopic image content, visual discomfort may still occur within this limit, and we believe three factors to be the most pertinent ones. The first factor is excessive demand of the accommodation-convergence linkage which potentially can be caused by fast motion in depth and is expected to become more severe with prolonged viewing and at short viewing distances. The second factor, 3D artefacts, results from insufficient depth information in the incoming data signal and yielding spatial and temporal inconsistencies, has not been subjected to much research yet, though inconsistencies, such as conflicts between different depth cues and geometrical distortions have already proved to cause annoyance and visual discomfort. The third factor concerns unnatural amounts of blur. Blur may cause ambiguous and unnatural depth percepts. The lack of blur, i.e., an entirely sharp image, can reduce the range of fusion, thereby causing fusion difficulties and depth cue conflicts. A surplus of blur resulting from crosstalk, 2D-to-3D conversion and artificially induced DOF, causes annoyance, visual discomfort and depth cue conflicts as well.

6. CONCLUSION

In this paper we have reviewed the concept of visual fatigue and its subjective counterpart, visual discomfort, in relation to stereoscopic display technology and image generation. To guarantee visual comfort in consumer applications, such as stereoscopic television, it is recommended to adhere to a limit of 'one degree of disparity', which still allows sufficient depth rendering for most application purposes. Within this zone of comfortable viewing, visual discomfort may still occur to an extent, however, which is likely to be caused by one or more of the following three factors: (1) excessive demand of accommodation-convergence linkage, e.g., by fast motion in depth, viewed at short distances, (2) 3D artefacts resulting from insufficient depth information in the incoming data signal yielding spatial and temporal inconsistencies, and (3) unnatural amounts of blur. In order to adequately characterize and understand visual fatigue and visual discomfort, multiple types of measurements, both objective and subjective, are needed.

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