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# Visual Discomfort and Visual Fatigue of Stereoscopic Displays: A Review

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**Abstract.** *Visual discomfort has been the subject of considerable research in relation to stereoscopic and autostereoscopic displays. In this paper, the importance of various causes and aspects of visual discomfort is clarified. When disparity values do not surpass a limit of 1°, which still provides sufficient range to allow satisfactory depth perception in stereoscopic television, classical determinants such as excessive binocular parallax and accommodation-vergence conflict appear to be of minor importance. 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) temporally changing demand of accommodation-vergence linkage, e.g., by fast motion in depth; (2) three-dimensional artifacts resulting from insufficient depth information in the incoming data signal yielding spatial and temporal inconsistencies; and (3) unnatural blur. In order to adequately characterize and understand visual discomfort, multiple types of measurements, both objective and subjective, are required.* © 2009 Society for Imaging Science and Technology.
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## 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.*"

The introduction of three-dimensional television (3D TV) to 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] For a successful market introduction, strain-free viewing must be guaranteed, and hence, both image quality and visual comfort must at least be comparable to conventional TV standards.[3] Since this promise has not yet been accomplished, extensive research to understand the factors underlying visual discomfort is needed. An overview of the current status of that research is provided in this paper. Literature in this area mention conflicts between accommodation and vergence, excessive binocular parallax and dichoptic errors as major problems potentially leading to visual discomfort. These factors are reviewed in this article, as well as some additional causes that have become more relevant nowadays with recent successive innovations in 3D imaging systems. Additionally, some experimental setup necessary to quantify the degree of visual discomfort in an unambiguous manner are discussed. Finally, a variety of measurement methods are addressed, which can roughly be divided into subjective measures (e.g., questionnaires and functional assessments) and objective measures, indicating the physiological state (e.g., optometric methods and brain activity measurements).

## HUMAN PERCEPTION OF DEPTH

### *Binocular Depth Perception*

Because our eyes are horizontally separated, each eye has its own perspective of the world, and thus both eyes receive slightly different 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 images and, from retinal disparity, i.e., the distance between corresponding points in these images, the brain extracts relative depth information. Even without benefit of stereopsis, depth can be perceived. This is based on monocular cues, such as perspective, interposition, or texture gradients. For

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[†]Portrayal of the enthusiasm around 1855 (see Ref. 1).

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an overview of the relative importance of different depth cues at various distances read.[4]

Points that are fixated by both eyes are projected onto corresponding parts of the retina. For any degree of vergence, the horopter is the surface in space that contains all points whose images stimulate corresponding retinal points; i.e., that all have zero retinal disparity. Points that do not fall on the horopter have retinal disparity. Points located in front of the horopter have a negative or crossed retinal disparity and points located behind the horopter have a positive or uncrossed retinal disparity. Panum's fusional area describes the small region around the horopter where sensoric fusion takes place; i.e., the neural process of merging the two retinal images into a single stereoscopic image. The receptive fields are relatively small at the fovea (central fusion) and relatively large in the periphery (peripheral fusion). Hence, the limits of Panum's fusional area are not constant over the retina, but expand at increasing eccentricity from the fovea. At the fovea sensoric fusion is limited to a retinal disparity of 0.1°, at an eccentricity of 6° to a retinal disparity of 0.33°[5,6] and at 12° of eccentricity to a retinal disparity of 0.66°.[6]

### *Ocular Near Triad*

Accommodation, vergence, and pupillary dynamics, i.e., the ocular near triad, continuously interact to control the functioning of the eyes.[7] To obtain clear, binocular single vision, 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 our eyes in opposite directions to locate the area of interest on the fovea and accommodation as alteration of the lens to obtain and maintain the area of interest focused on the fovea. The interaction between accommodation and vergence is accompanied by changes in pupil diameter. The pupil constricts with near vergence/accommodation to compensate for a narrow depth of field and increased spherical aberration, and dilates with far vergence/accommodation to reduce diffraction and increase retinal illumination.[5] The pupillary dynamics are governed by the autonomic nervous system and reflect mental activity. As such, they may indicate visual discomfort.[8,9] As part of the ocular near triad changes in pupil diameter may affect accommodation and vergence.

### *Depth of Focus*

Our eyes can tolerate small amounts of retinal defocus without adjusting accommodation to perceive a sharp image. The depth of focus (DOF) describes the amount of retinal defocus in which accommodation does not change while objects are perceived clearly.[10,11] DOF can be defined as "the variation in image distance of a lens or optical system which can be tolerated without incurring an objectionable lack of sharpness in focus."[12] Hence, each single eye has a DOF; it does not depend on stereoscopic vision, but it simply defines the zone in which vision is sharpest and deviations in either direction gradually decrease image quality by the introduction of blur.[13] For a review that covers the DOF, we refer to Wang and Ciufredda.[12] They illustrate that the range of DOF is influenced by many factors, of which some are related to target attributes, e.g., contrast, luminance, and spatial frequency, and some to eye/brain attributes; e.g., pupil size and age. The DOF ranges from 0.04 to 3.50 diopter, with typical values of approximately 0.2 to 0.5 diopter.

### *The Accommodation-Vergence Model*

Vergence and accommodation are generally modeled as two dual parallel feedback control systems that interact via crosslinks as depicted in Figure 1.[14–17] Accommodation is primarily retinal blur-driven and vergence primarily retinal disparity-driven and both systems respond to proximity information, i.e., apparent target nearness, such as "pictorial" depth cues and motion-in-depth cues. Each system includes a tonic component, i.e., an adaptive component, which accounts for slower adaptations to altered viewing situations. Both systems interact via reflexive cross-link interactions. The gains of the cross-link interactions are described by the AC/A ratio (i.e., the change in vergence due to accommodation per change in accommodation in the absence of retinal disparity) and the CA/C ratio (i.e., the change in accommodation due to vergence per change in vergence in the absence of blur).

### *Depth Cue Integration*

To provide an accurate, consistent, and useful percept of the physical environment, the visual system must rely on and reduce ambiguity by the combination of different depth cues. It remains an ongoing debate which strategy the brain uses to extract 3D depth from optical information in two 2D retinal images.[18] A single unified theory about cue integration is not yet established. Recent research has conceptualized depth cue integration as a problem of statistical inference; i.e., the maximum-likelihood estimation of cue combination based on the reliability of the cues.[19] In stereoscopic displays conflicting cues may be introduced, and it may be even more interesting and important to investigate how the visual system resolves such conflicts. For example, it has been reported that perceived depth decreased when ordinal configural information (i.e., familiarity and convexity) and retinal disparity were inconsistent.[20] Yet, the impact on visual comfort was not addressed.

### *Individual Differences*

People differ in human visual system characteristics, which directly determine their ability to perceive stereoscopic depth. One of those characteristics is the interpupillary distance (IPD). People with a small IPD perceive more stereoscopic depth for a fixed set of objects at a fixed viewing distance than people with a large IPD. As such, for a fixed screen disparity, i.e., the distance between two corresponding pixels in two separate views on a stereoscopic display, people with a smaller IPD reach fusional limits more rapidly. 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. To include extremes and children, a range of 40 to 80 mm is recommended.[21]

Visual disorders in early childhood, even if only temporary, may result in stereo blindness, which is estimated to

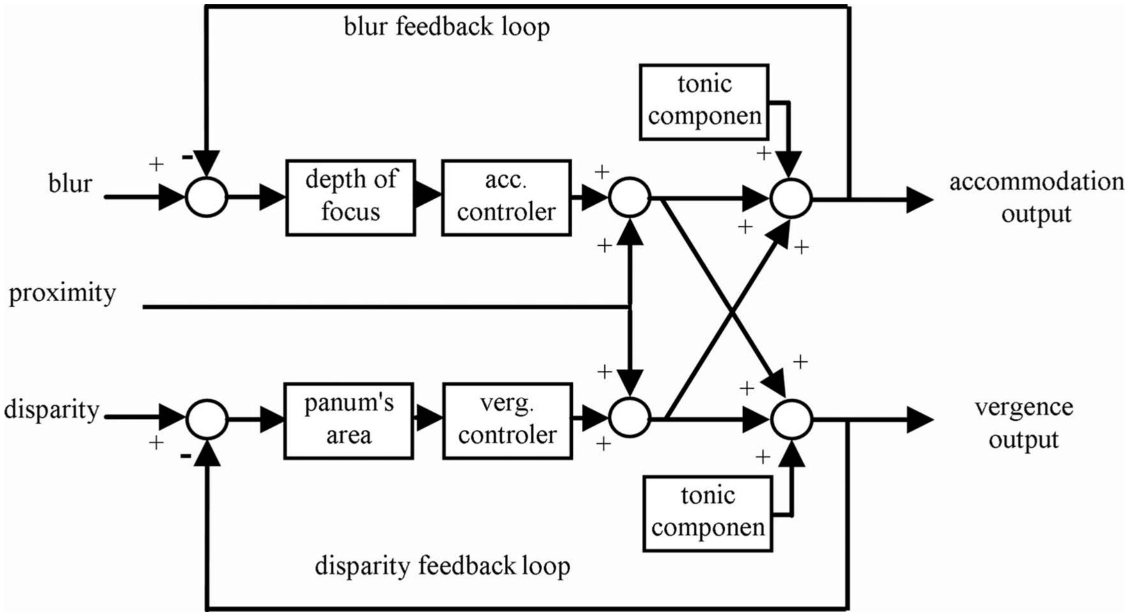


Figure 1. Accommodation and vergence modeled as two dual parallel feedback control systems that interact via cross-links (Refs. 14–17). Accommodation depends on defocus, proximity, tonic adaptation, and vergence-accommodation. Vergence depends on retinal disparity, proximity, tonic adaptation, and accommodative-vergence. Both systems also provide negative feedback to the input stimuli to obtain stable states. The accommodation-vergence system can be explained as follows. Under natural viewing conditions, accommodation and vergence interact to provide comfortable and clear, binocular, single vision. Small degrees of retinal defocus within the DOF do not drive the accommodation system, and small retinal disparities are fused by sensoric fusion and do not drive motoric fusion; i.e., vergence movements. As an object approaches, changes in blur that exceed DOF drive the accommodation controller and changes in retinal disparity that exceed Panum's fusional area drive the vergence controller. The summed output of the controller, the proximal component, the tonic component, and the cross-link describes the overall system's response and provides negative feedback to the input stimuli to obtain a stable state.

affect 5–10% of the population. Richards in 1970 performed a survey among 150 participants and found that 4% were unable to perceive a hidden Julesz figure in a random-dot stereogram, and 10% had great difficulty detecting its direction relative to the background.[22] Visual abilities also vary with age as a result of changes in the structure of the eye. Accommodative ability decreases with age, with a decline starting at 40 years up to about 55 years of age, when little or no accommodation remains.[23] Conversely, the visual system of children still has a high degree of plasticity, because it is not fully developed until the age of 7.[16] Moreover, as a result of their small IPD, the impact of too much screen disparity is larger for children than for adults. Research also revealed that once some visual disorders are established during childhood, such as myopia that is often related to near work, the degree of the disorder typically increases.[24] This is the main reason some researchers advise against stereoscopic viewing on displays by children, stating that even though little evidence exists that viewing stereoscopic content causes permanent damage to the visual system, there is also no evidence that contradicts this argument.

## VISUAL FATIGUE AND VISUAL DISCOMFORT

Over the last decades, safety and health issues related to video display terminals (VDTs) in general, and stereoscopic displays in specific, have been extensively studied. Particularly for stereoscopic displays, visual discomfort is mentioned in the literature as one of the important health issues. Hence, for the realization of a comfortable viewing experience on a stereoscopic display, an all-inclusive study of visual discomfort is required.

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

The all-embracing diagnostic term for visual fatigue and visual discomfort is asthenopia and literally means "eye without strength."[25] Asthenopia may be concentrated around the eyes, or may be diffuse as a general headache, or may occur in the neck and shoulders. Much research has been conducted in the past concerning asthenopia, though it seems that the current topics of research such as conceptualizing, measuring, and preventing asthenopia to a large extent resemble the pioneering work in the early 1900s.[26] Its conceptualization remains ambiguous; different definitions are used across different fields, but no absolute definition exists. In most cases asthenopia is conceptualized as a combination of underlying determinants and symptoms, or by a substitution such as eyestrain.[27,28] Although eyestrain is nearly synonymous with the objective component of asthenopia, i.e., visual fatigue,[27] for clarification in this research a distinction is made. Eyestrain is defined as "the symptoms experienced in the conscious striving of the visual apparatus to clarify vision by ineffectual adjustments."[29] It refers to a specific aspect of the visual system; i.e., continuously resolving ineffectual adjustments. Visual fatigue refers to any visual dysfunction resulting from the use of one's eyes. As such, visual fatigue includes such continuous ineffective adjustments, as well as conflicting or problematic, functional adapted states of the visual system. Hence, visual fatigue is defined as physiological strain or stress resulting from exertion of the visual system.

The determinants of asthenopia are very diverse, and, therefore, are still a source of ongoing research. In the area of VDT, asthenopia can be caused or induced by anomalies of vision such as heterophoria, vergence insufficiency, or accommodative dysfunction. Additionally, it can be related to display issues such as compromised quality of the viewed image, flickering stimuli, suboptimal gaze angles, or viewing distance.[27,30] Research concentrated on stereoscopic displays revealed that causes of asthenopia include: (1) anomalies of binocular vision; (2) dichoptic errors, such as geometrical distortions between the left and right images (e.g., keystone distortion, depth-plane curvature, crosstalk, and binocular rivalry); (3) conflict between vergence eye movement and accommodation; and (4) excessive binocular parallax.[11,31–35]

Directly related to the extensive list of determinants is the amount and diversity of symptoms of asthenopia. To give a clear overview, the various symptoms[27,28,30,31,36] are grouped according to a specific classification provided by Sheedy, Hayes, and Engle.[27] They applied a factor analysis to different symptoms and revealed two latent factors, internal and external factors, that can be differentiated by sensation type, sensation location, and induced condition. The internal factors include ache, strain, and headache, and denote symptoms located behind the eyes. The external factors include burning, tearing, irritation, and dryness, and denote symptoms located in front of the eyes.

Consequently, the multiple determinants and symptoms result in numerous and widespread indicators to measure the degree of asthenopia. An essential issue in the determination of asthenopia is that sensations or symptoms can refer to different stimulated anatomical locations. A single underlying factor, e.g., vergence insufficiency, can stimulate anatomical locations such as medial ocular muscles, accommodation of the ciliary body and the tear-gland. Stimulation of each of these will probably result in a different sensation, yet all are due to the same primary underlying determinant.[27] Hence, the concept of visual fatigue cannot be evaluated with only one objective indicator. In addition, many of the ocular changes representing visual fatigue can also be regarded as healthy characteristics of our biological system adapting to altered visual environments. The occurrence of visual discomfort also needs to be verified. Only physiological changes that are accompanied by negative psychological effects in function or comfort should be critically examined for their magnitude and subjective impact. Though our visual system adapts and may prevent psychological effects from occurring in the short term, their impact may increase in strength after prolonged viewing of stereoscopic content. Hence, the effects of a prolonged period of viewing are also of interest here and should be critically examined for their magnitude and subjective impact. Therefore, 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 discomfort in a sensitive, accurate, reliable, and valid way for both short- and long-term viewing. The section on Measurement Methods, below, provides an extensive description of these different measurement methods.

## DETERMINANTS: AN EMPIRICAL DESCRIPTION

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. Part of the reason for this was increased competition from other immersive cinema formats. Undeniably, however, some of the problems with 3D cinema appeared to be associated with issues of visual discomfort.[2] In the next section we describe factors that are thought to cause visual discomfort in stereoscopic displays nowadays. These factors are discussed from an empirical point of view in which a distinction between objective visual fatigue and subjective visual comfort is applied.

### *Excessive Screen Disparity*

As discussed previously, sensoric fusion limits can be remarkably small. Without vergence movements and for brief stimulus durations, fusion limits as small as 27 min of arc for crossed and 24 min of arc for uncrossed retinal disparity are found.[37] Many factors affect the limits of fusion, including eye movements, stimulus properties, temporal modulation of retinal disparity information, exposure duration, amount of illuminance, and individual differences. The limits of fusion decrease with smaller, detailed, and stationary objects and increase with larger, moving objects and the addition of peripheral objects to the fixation object.[6,18,37–40] With longer stimulus durations and vergence eye movements, retinal disparities as large as 4.93° for crossed and 1.57° for uncrossed disparity can be brought into fusion range without diplopia.[37]

However, the classical notion of Panum's fusional area has only limited applicability in establishing absolute limits for screen disparities in stereoscopic displays. A distinction between absolute and relative screen disparity is useful in this sense. The absolute screen disparity refers to a disparity-offset of the whole retinal image of one eye relative to the other, whereas the relative screen disparity refers to the disparity differences between objects within the retinal images. The absolute screen disparity can be large and can be overcome by appropriate vergence movements, yet clear, single binocular vision can only be perceived as long as the relative screen disparities remain within the fusion range.

### *Accommodation and Vergence Mismatch*

The mismatch between accommodation and vergence arises due to an intrinsic conflict between the accommodative stimulus that remains fixed on the stereoscopic screen where the image is displayed the sharpest, and the vergence stimulus that may fluctuate in depth depending on the degree and the sign of screen disparity. Since accommodation and vergence are reflexively coupled mechanisms, their artificial decoupling when viewing stereoscopic displays has often been theorized as a significant factor underlying the occurrence of visual discomfort.[31,35,41,42] Eadie et al. revealed that stereoscopic stimuli can initiate changes in the cross-link interaction between vergence and accommodation, i.e., altered AC/A and CA/C ratios, as well as in the tonic components.[17] These changes can have negative consequences for clear and single binocular vision, because changes in the optical alignment of the eyes affect binocular fusion limits and depth perception.[43,44] Such alterations may last minutes or even hours, because re-adaptation to the real world is needed.[5] Although it is argued that this process of decoupling accommodation and vergence induces visual fatigue, research reveals contradictory results in that accommodation does not remain focused on the screen, but shifts towards the reconstituted object.[9,45] It remains unclear, however, whether the shift of accommodation from the display plane was elicited by vergence-driven accommodation, or that it was a natural underaccommodation that occurs in most people during near work.[24] Hence, suspicions arise as to whether a conflict between accommodation and vergence occurs at all as a result of this mismatch and how it is related to the DOF of the eye.[10] Fig. 1 provides clarification. If screen disparity is increased, the retinal disparity of the reconstituted object surpasses Panum's fusional area. Vergence movements relocate the retinal disparity within Panum's fusional area and as such, increase fusion limits (i.e., motoric fusion). As a consequence, accommodation shifts away from the display under the influence of vergence-driven accommodation. As long as the accommodation shift remains within the DOF, accommodation is able to focus the reconstituted object sharply on the retina.[46] If screen disparity is increased up to an amount at which the resulting retinal defocus cannot be accounted for by the DOF, negative accommodation feedback directs accommodation and vergence (via accommodative-vergence) towards the display, thus away from the reconstituted object. As such, the accommodation response conflicts with the vergence response. The accommodation-vergence system is able to cope for some degree of such a conflict, i.e., stereoscopic images are perceived sharply and fusion is preserved, but operates under stress and viewers experience visual discomfort. Especially in case of prolonged viewing, the visual discomfort may increase. The ranges of accommodation and vergence that can be achieved without any excessive errors in either direction are referred to as "the zone of clear single binocular vision,"[5] If the conflict between the accommodation and vergence increases even more, three errors can occur: loss of accommodation resulting in a blurred image, loss of fusion resulting in double vision, or both.

### *Zone of Comfortable Viewing*

The limits of the accommodative output under natural viewing conditions, i.e., range of DOF, concur with the range of fusion.[41,47–49] Objects at increasing distance from the fixation point are perceived as more blurred. As a consequence of this blur, diplopia is postponed, because the limits of fusion increase as a 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 and together define a zone of comfortable viewing.

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.[15,35] With respect to the revisited Panum's fusion area, i.e., under natural viewing conditions, retinal disparities beyond 1° (a conservative application of the 60 to 70 arcmin recommendation[33,48]) are assumed to cause visual discomfort. This 1° is calculated from the characteristics of DOF.[48] This estimate nowadays serves as a rule-of-thumb, but it is acknowledged here as a limit for a zone of comfortable viewing, despite the fact that lower recommendations have also been reported.[34,50] This 1° limits the screen disparity, and as such imposes restrictions on the generation of 3D content. In the case of 3D TV, one popular acknowledged format for stereoscopic content is defined as a red-green-blue (RGB) image with one or more corresponding depth maps.[51,52] The first, and most important depth map is a gray-scale image, in which the gray value per pixel indicates the relative depth of each corresponding RGB pixel (secondary depth maps may contain additional depth information, e.g., occlusion information). The resulting amount of screen disparity can be set and altered by varying offset and gain factors, when rendering the left and right views calculated from the depth maps on the display.

For the vergence system a zone of comfort proposed by Percival could be considered as an alternative for the 1° limit. It is defined as the middle third of the amount of binocular vergence with almost no change in accommodation, i.e., the middle third of "the zone of clear, single binocular vision,"[53] which can be derived from Morgan's normal population norms.[54,55] These zones are depicted in Figure 2, including the viewing zone covered by the 1° disparity limit. The limits of "the zone of clear, single binocular vision" or motoric fusion limits are generally established by increasing prism load and measuring blur and break points, i.e., the prism loads at which blurred vision or diplopia is perceived, respectively, in both convergent and divergent directions.[56] Note that Fig. 2 depicts two Percival areas of comfort due to a lack of consensus in the method of determining Percival's area within the display research area. In some research the break points are used as motoric fusion limits,[31] whereas in other research blur points are used.[54] Percival himself stated the use of the blur points as limits of "the zone of clear, single binocular vision" (cited by Sheard).[53]

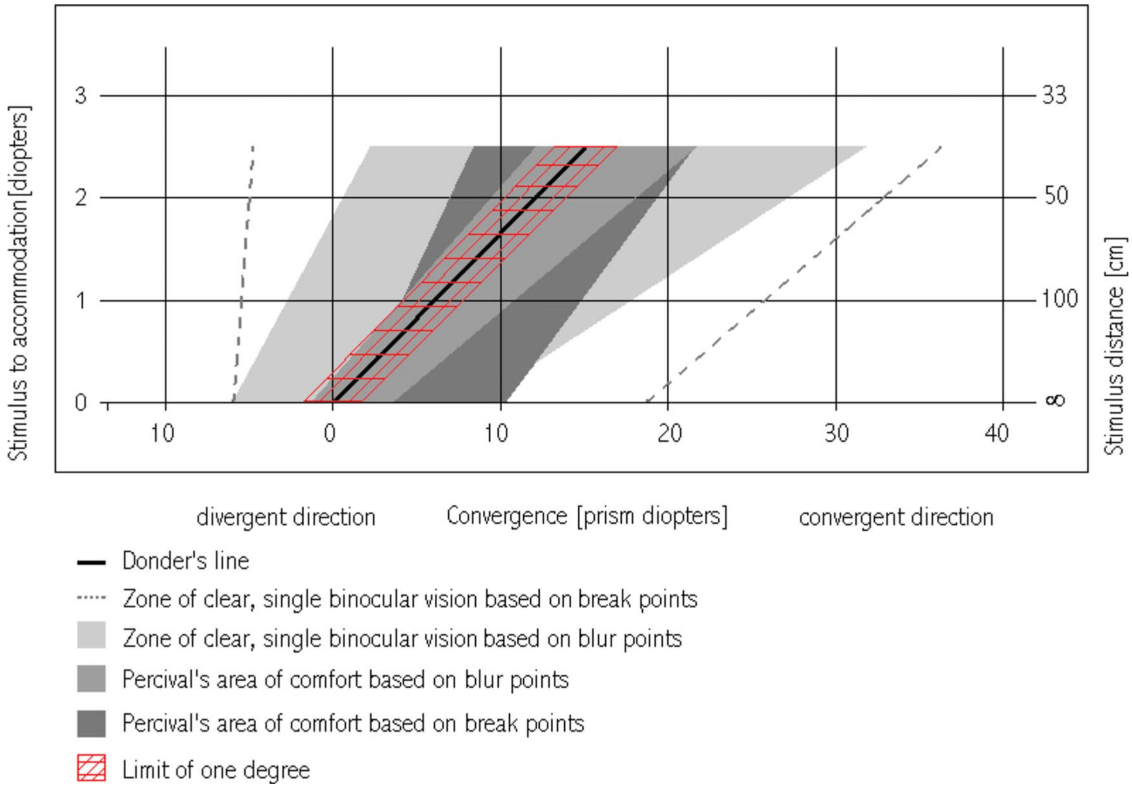


Figure 2. Different viewing zones with respect to comfortable viewing; "the zone of clear, single binocular vision" (Ref. 53), two different areas of comfort defined by Percival's criterion, one based on blur points (Ref. 53 and one based on break points (Refs. 30 and 55 and the zone formed by the 1° limit. The black solid line depicts Donder's line (Refs. 10, 30, and 55).

Previous research already related Percival's area of comfort to stereoscopic viewing,[31,35] yet a few aspects reveal that Percival's area of comfort cannot be simply applied to stereoscopic displays. The first aspect is that Percival's area of comfort is determined by the use of prisms and obtaining stereoscopic content through the use of prisms perceptually differs from the use of stereoscopic displays.[11] Prism loads relate to motoric fusion and change the whole visual field, i.e., absolute disparity, in contrast to only the screen disparity of certain objects in a stereoscopic image, i.e., relative disparity. As stated before, for 3D TV applications with the RGB plus depth format, the screen disparity is calculated from depth maps containing relative depth information. A second aspect is that the size of Percival's area depends on the viewing distance as depicted in Fig. 2. For long viewing distances, Percival's zone of comfort does not include the display plane (on Donder's line, i.e., the line that represents the perfect amount of vergence required for each level of accommodation for single binocular vision) when based on breakpoints according Morgan's normal population norms.[54–56] And for short viewing distances, tolerances for prism loads, based on Morgan's normal population norms, are larger than our tolerances for short viewing distances. A third aspect is that people might adapt to changes in prism load, i.e., prism adaptation.

We argue for application of a screen disparity of 1°, in both divergent and convergent directions from the display plane, as a limit for a zone of comfort. Table I which presents theoretical values for comfortable viewing expressed in distances for different viewing distances based on this limit. Note that although this limit is valid in theory, in practice no 3D display can display the amount of depth at large viewing distances that results from 1° of disparity. Hence, the 1° limit can be applied as a general limit of comfort for stereoscopic displays measured from the display plane, excluding the extensive list of factors that underlies the limit.

To accept this 1° limit as an applicable boundary for a zone of comfortable viewing, it is necessary to demonstrate and verify that stereoscopic image content beyond this limit results in asthenopia in contrast to within this limit. At

**Table I.** Limits of comfortable viewing at different viewing distances corresponding to one degree of screen disparity for both crossed and uncrossed disparity. The limits set the area around the display measured from the viewer.

| | Limits for comfortable viewing | |
|---|---|---|
| View distance (mm) | Near (mm) | Far (mm) |
| 500 | 440 | 580 |
| 1000 | 780 | 1400 |
| 2000 | 1300 | 4800 |
| 3000 | 1600 | 23000 |

larger screen disparities stereoscopic content is perceived sharply and fusion is preserved, though accompanied by the occurrence of asthenopia as a result of the increasing stress on the visual system, up to a point at which blur and double vision are perceived. A blurred image is expected to occur before a double image, as vergence seems to be dominant over accommodation, i.e., the visual system has a preference in avoiding diplopia before blurring.[57]

*Beyond the Zone of Comfortable Viewing*

At increasing screen disparities beyond 1°, the oculomotor system operates under increasing stress to preserve fusion and provide sharply focused images. This statement was confirmed by Ukai and Kato, who recorded the dynamic behavior of the ocular near triad of participants viewing stereoscopic images.[8] The screen disparity of a stereoscopic stimulus was increased stepwise from 0 to 1.6°, 2.1° or 2.6°. Vergence was evoked to preserve fusion and accommodation was elicited under the influence of vergence-accommodation away from the screen. This initial accommodation response, however, was followed by a correction in the opposite direction by the accommodation controller. For the step in screen disparity of 2.1°, this correction was sufficient to correct the vergence response under the influence of accommodative-vergence. For the step in screen disparity of 2.6°, however, the correction responses of accommodation and vergence repeated themselves and both systems became unstable and oscillated. Whether the conflict between accommodation and vergence resulted in double or blurred images was not verified. Okada et al. revealed that when the accommodation-vergence system operates under stress, it continuously tries to find a more stable and less stressful state.[42] Stereoscopic stimuli were varied by different levels of blur (i.e., accommodation) and different degrees of screen disparity (i.e., vergence). A shift in accommodation occurred towards the 3D stimulus under the influence of vergence-driven accommodation that increased systematically with increased degrees of blur. This indicates a conflict between accommodation and vergence for sharp images displayed at screen disparities beyond the 1° limit; the accommodation-vergence system is able to operate under stress, CA/C ratios adapt and cross-coupling still occurs, but continuously tries to resolve the stress. Hoffman et al. constructed a multifocal 3D display with separate left and right-eye views per focal plane, enabling separate stimulation of vergence and accommodation for different focal distances.[35] Stereoscopic stimuli were presented with various vergence and accommodation distances, from which two-thirds of the distances were conflicting (ranging from 0.33 diopter to 1.33 diopters). A questionnaire that followed an orientation detection task significantly indicated more visual discomfort for conflicting stimuli than for the nonconflicting ones. Nojiri et al. verified that stereoscopic stills with large parts of the images perceived beyond the DOF, received much lower scores in terms of visual comfort in contrast to stereoscopic stills perceived within the DOF.[58] Objective measurements were not performed, therefore these finding could not be supported objectively. Yano et al. evaluated comfortable viewing for still images in relation to the range of screen disparity both subjectively, using a self-assessment test, and objectively, with pre- and post-accommodation responses.[11] The subjective evaluation revealed higher values for visual discomfort when images were displayed beyond 1° of screen disparity, which was confirmed by their objective measurements.

*Within the Zone of Comfortable Viewing*

Within the zone of comfortable viewing, visual discomfort should not occur. Indeed, most stereoscopic stills are comfortable to view, nonetheless, visual discomfort might occur as a consequence of much variation in screen disparity within this zone.[58,59] Yano et al. confirmed this finding with stereoscopic sequences.[60] A continuous subjective assessment revealed that visual discomfort was related to image content: visual comfort received local low evaluation scores for scenes with high degrees of screen disparity and high amounts of motion. In line with these findings, a follow-up experiment confirmed that discrete changes of motion in the depth direction in stereoscopic sequences resulted in a decrease of the accommodation response and a significant decrease of visual comfort.[11] Another study evaluated the effect of vergence load on Percival's area of comfort.[31] Though stereoscopic viewing through prisms differs from stereoscopic content on a 3D display, it does affect the accommodation-vergence linkage. Vergence loads within Percival's area of comfort induced a lower degree of discomfort than loads outside this area. Temporally changing visual fields within this area, however, reduced the relative vergence limits, increased the latency of visually evoked cortical potentials, and affected accommodation responses, but were subjectively not reported as yielding visual discomfort. To further clarify the effect on visual discomfort of changing screen disparity magnitudes in time, relationships among the amount of screen disparity, object motion, and visual comfort were verified.[33] Results revealed that periodically changing screen disparity from crossed to uncrossed as well as the rate of this change influenced visual comfort to a larger extent than the amount of disparity, even when it surpassed the 1° limit.

It seems that visual discomfort increases when the demand on the oculomotor system increases as well. This occurs with screen disparities beyond 1° and with motion in the depth direction within the zone of comfortable viewing. It is expected that prolonged viewing, which exhaust the oculomotor system, and viewing at short distances, which increases the relative exertion of accommodation, result in a further increase in visual demand, and thus in more visual discomfort. More detailed research is needed to entirely clarify the relationship between accommodation and vergence with dynamic stereoscopic sequences within the DOF.

***Stereoscopic Distortions***

Stereoscopic distortions result from several stages in the creation process of 3D content, namely, content generation (choice of camera, camera configuration, two (2D)- to three-dimensional conversion), coding and transmission (compression), rendering (multiple views rendered from a single view), and type of display. The literature describes several types of distortions that can induce visual discomfort and can occur simultaneously.[34] Generation-related distortions include keystone distortion, depth-plane curvature, puppet thearte effect, cardboard effect, and shear distortion. Display-related distortions include picket fence effect, image flipping, and crosstalk. They are not all discussed 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 by IJsselsteijn et al.[32] As crosstalk is an artifact that to some extent appears in nearly any 3D display, it is briefly discussed separately.

Research mentioned crosstalk as the main display-related perceptual factor degrading image quality and causing visual discomfort.[32,34] Crosstalk is an artifact that results from the imperfect separation of the left- and right-eye views. It is used interchangeably with ghosting, though crosstalk denotes the electrical or optical mixing of left- and right-eye images,[61] which may result in perceived ghosting, but also in blurring. In some cases, however, crosstalk may also have some beneficial effect on image quality and visual comfort. Some autostereoscopic multiview 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 screen 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.[61] Nonetheless, perception of depth is preserved. Furthermore, because crosstalk results in blurred objects to an extent related to their amount of screen disparity, it decreases the accommodation stimulus and as such, the accommodation-vergence conflict. On the other hand, blur is stated as one of the most important factors that determine viewing comfort.[62] Hence, 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.

### *An Artificial DOF*

In real world situations, objects at distances both in front and behind the fixation point are blurred to extents proportional to this distance, which if large enough, does not stimulate fusion. Blur in this sense may be defined as the perception of retinal defocus[12] and is a direct stimulus for accommodation. Sharpness enhancement nowadays is often implemented in display systems to improve image quality. Though a positive development, the lack of blur may cause visual discomfort: (1) because a stronger accommodation stimulus increases the accommodation-vergence conflict,[43,44] and (2) because objects with a screen disparity beyond the fusion limit still elicit an effort to fuse, while fusion is not possible due to the large retinal disparity.[63]

Simulating DOF is said to minimize both these problems and to provide a more natural percept. 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 reduce the conflict between accommodation and vergence. To conform to reality and avoid annoyance, objects fixated on must be displayed fully sharp, whereas other regions must have a depth-dependent blurriness to preserve fusion of excessive parallax. This requires object-dependent depth information. Three essential steps are required for proper implementation of a simulated DOF: localization of the eye positions,[63] determination of the fixation point,[63] and implementation of blur filters to nonfixated layers.[64] However, this procedure may also induce negative side effects. First, our visual system generally does not integrate retinal disparity and high amounts of blur, since they are active over different ranges.[65] When the visual system is forced to do so, simulating DOF could lead to unnatural or uncomfortable viewing. Second, incorrect blurring of objects and edges may facilitate ambiguous depth perception. The amount of blur depends on the viewing distance and the polarity of the depth percept; i.e., in front and behind the fixation point. Different viewing distances and polarities can induce similar retinal defocus and as such, incorrect accommodation responses. Third, simulating such a DOF may have practical limitations with some autostereoscopic display technologies; e.g., in the case of multiple viewers that may concentrate on different parts of the image. Other research has applied a different approach.[50,66] To avoid the entire tracking procedure, another solution is to scale the scene depth range to our perceivable depth range. However, compressing or expanding the scene depth range may result in unnatural depth perception. An improved approach was introduced that compressed only the most outer regions; i.e., not the region of interest.[66] The solution has been implemented, but not yet evaluated on a perceptual base.

### *3D Artifacts*

To guarantee sufficient 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 and that a good depth impression on screen will suffice. This quasi depth ordering process relies on assumptions, estimations, and heuristic cues.[67–69] These processes can result in artifacts that include spatial and temporal inconsistencies, e.g., objects or parts of objects that are assigned incorrect depth values and, therefore, are 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. Image content that is unavailable in the original 2D image because it is hidden behind occluding objects, suddenly becomes visible in any of the virtual views. Since no information of the occluded objects is available in the original image content, the missing areas (often referred to as *holes*), must be replaced with "useful" color information.[70] Different algorithms have been proposed for this hole-filling procedure,[70–72] yet all experience the same shortcoming, namely that the occluded area is never fully correct, but always interpolated from existing information. Hence, 2D-to-3D conversion cannot be fully accurate, and artifacts related specifically to the 2D-to-3D conversion and rendering process are likely to occur. Little is known about the impact of these artifacts on visual discomfort. In the case of misallocated objects, for example, cue conflicts may occur between our stereopsis and other depth cues like familiarity. These conflicts are at least perceptually annoying, but when the visual system cannot satisfactorily resolve them, they are expected to cause visual fatigue as well.

## MEASUREMENT METHODS

The indicators for measuring visual fatigue and visual discomfort are numerous and widespread.[27,30] They can be clustered into objective indicators for visual fatigue and subjective indicators for visual comfort. This section provides a more thorough elaboration of measurement methods and devices that are believed either to be suitable or promising in determining the degree of visual fatigue or visual discomfort.

### *Subjective Measurement Methods*

Subjective assessment methods as a means to perceptually evaluate stereoscopic (as well as monoscopic) content are nowadays widely accepted and applied.[11,31,33,62] Visual discomfort and its dependence on individuals' self-appraisal must be evaluated on a perceptual basis.[3,62] Three subjective methods can be distinguished; namely, explorative studies, psychophysical scaling, and questionnaires. According to Meesters et al.,[3] explorative studies can be used in the context of stereoscopic displays to: (1) generate evoked unprimed perceptions, (2) evaluate the added value of stereoscopic displays both with and without predefined criteria, and (3) determine the attributes that underlie multidimensional concepts such as visual discomfort. Psychophysical scaling enables engineers to enhance and optimize their systems based on quantified perceptual attributes such as image quality and visual discomfort. Two types of applications can be distinguished, each with their own measurements methods. The first is performance oriented; i.e., used to facilitate a certain task. The second is appreciation oriented; i.e., used to establish a degree of appreciation. Recommendations for appreciation-oriented applications for stereoscopic displays are described in recommendations such as ITU-R BT.1438 [73] and ITU-R BT.500.[74]

Questionnaires have been extensively applied as a specific means to determine the degree of visual discomfort.[10,27,31,75] To our knowledge, a generally accepted questionnaire that proved to be valid, sensitive, reliable, and robust in determining the degree of visual discomfort of stereoscopic displays has not yet been established. In clinical research, questionnaires are able to evaluate the degree of asthenopia due to visual deficits. In most cases these questionnaires are too extended for our purpose, since the assessment incorporates a wide range of mental, social, and physiological aspects. In order to develop a questionnaire that measures the degree of visual discomfort caused by viewing stereoscopic content, consultation with clinical and eye care experts and interviews with users is required.[76] Furthermore, questionnaires able to evaluate the degree of specific visual deficits resulting in visual discomfort must also be taken into account. Sheedy et al. developed a questionnaire to measure the degree of asthenopia, but it is not specifically related to stereoscopic displays.[27] We believe that any questionnaire evaluating stereoscopic content should incorporate as a minimum all the items that have been used in Sheedy et al.'s questionnaire: tired eyes, uncomfortable vision, headache, ache in or behind the eyes, eye irritation, pulling feeling of the eyes, blurred vision, dryness of the eyes, burning eyes, stress, neck pain, and watery eyes. Depending on the purpose and application (e.g., stereoscopic computer games[77] or stereoscopic mobile phone usage[78]), it might be useful to include additional background information such as previous experience with similar applications or amount of near work during a typical day.

### *Objective Measurement Methods*

The many indicators for visual fatigue are related to alterations in various characteristics of different visual functions (e.g., accommodative and vergence responses, pupillary dynamics, AC/A and CA/C ratios, fusion reserves, visual and stereo acuity, and heterophoria). Alterations to these indicators can be quantified by implementing three different classes of measurements. The first class includes optometric instrument based measurements that directly measure the indicators with optical instruments such as refractometers and pupil trackers. The second class consists of optometric clinical based measurements that indirectly measure the indicators via prisms, lenses, or vision charts. The third class contains brain activity measurements in which indicators are measured as a result of brain activity.

#### *Optometric Instrument Based Measurements*

In many studies, optometric devices have been applied in pre- and post-tests to determine the amount of change of an indicator for visual fatigue as a result of viewing stereoscopic content.[11,31,60] Binocular single vision and asthenopia have been related, however, to various aspects of the dynamics of the ocular triad. It is difficult to draw solid conclusions without simultaneous, continuous, and direct measurement of the ocular triad of participants that are viewing stereoscopic content.[8,42,44] A variety of commercially available oculomotor measurement devices are able to measure different parameters of the oculomotor system. The most familiar one is the autorefractor: an effective tool for measuring various aspects of the dynamic accommodative response and the objective refractive error of the eye. A major drawback of refractors is the inability to simultaneously measure the oculomotor triad dynamics.[79] Hunt et al. address photoretinoscopy, more specifically, the PowerRefractor™, as unique in allowing measurement of the oculomotor triad in both eyes simultaneously, continuously and remotely in a nonobtrusive manner.[80] Comparisons with clinical methods and the more established open view autorefractors (e.g., the Nidek AR600-A and the Shin-Nippon SRW-5000) showed a similar average accuracy of accommodation measurement.[80,81] The PowerRefractor has the advantage of open viewing; i.e., allows an open field of view for natural binocular viewing without obtrusion of the device. As such, it can be used without a bite-bar or head strip, and allows easier use for measurement on visual systems of children or other less cooperative participants as well as a wider range of experimental applications. However, the accuracy of approximately 2° of disparity for vergence measurements is too coarse to measure the effects of changes within the zone of comfortable viewing. Other solutions are "simply" to combine an autorefractor with an eye tracking device to simultaneously record vergence eye movements and accommodation dynamics. Okada et al.[42] applied a tracker on the left eye and a Shin-Nippon SRW-5000 on the right eye and Suryakumar et al.[79,82] used a stereo eye tracker in synchronization with a custom built photorefractor allowing simultaneous high speed measurements of both vergence and accommodation. In general, optometric measurements are costly, time-consuming, and are usually conducted with only small numbers of participants.

*Optometric Clinically Based Measurements*

Clinical diagnoses to investigate and diagnose the degree of (binocular) visual anomalies are applied to patients who suffer from asthenopic complaints such as headaches or problems with focusing. These measurements are relatively cheap, concise, noninterventional, quantitative with a high sensitivity and specificity, and applicable to a large group of participants. The number and diversity of clinical tests to detect specific visual deficits is enormous.[55,56] However, due to an expected rapid reduction in the degree of visual fatigue after viewing stereoscopic content, only a small set of clinical tests able to diagnose the degree of visual fatigue with a fast measurement are useful. The following measurement protocol is proposed: (1) describe the general visual function of the participants in the unaffected state with the aim of establishing individual differences in visual aberrations and sensitivities, and (2) apply a set of clinical pre- and post-tests to determine possible alteration of the visual functions, i.e., the difference between the unaffected (pre-test) and the affected (post-test) state of certain visual functions, as a result of viewing stereoscopic displays.

The first step is a thorough optometric screening of participants in order to distinguish participants with normal vision from those with visual deficits. Both groups can serve different purposes; the group with visual deficits is more susceptible to visual fatigue, which is interesting from a clinical point of view. The group with normal vision reflects the visual behavior of the majority of the population, which is interesting from a consumer's point of view. The screening also serves as a potential clarification for individual differences in the subsequent pre- and post-tests. It should include indicators such as visual acuity, stereo acuity, convergence ability, and AC/A ratio.

The second step, i.e., a reliable and valid set of clinical pre- and post-tests, to our knowledge has not yet been established for stereoscopic displays. Assuming a difference between monoscopic and stereoscopic viewing, not all tests are equally appropriate to diagnose the effect of stereoscopic viewing. A few aspects should be accounted for when composing such a set. First, in order to address the impact of binocular depth on the visual system, a test should be able to distinguish conventional monoscopic viewing conditions from stereoscopic viewing conditions. Second, the tests should be executed as quickly as possible, which constrains the length of the test. Third, ideally the set of tests should be applicable to all different types of display, including autostereoscopic systems, and systems based on polaroid or shutter glasses. However, it is highly plausible that different displays, incorporating different principles of generating depth, affect the visual system differently. For example, measuring fusional amplitudes may be less relevant than measuring accommodation response for autostereoscopic displays, which as a result of crosstalk, are limited in their amount of depth, but introduce high amounts of blur. Fourth, the display application should also be taken into account as it is expected that vergence measurements are suitable for both desktop and TV applications, i.e., for short and long viewing distances, respectively, yet accommodation only for desktop applications.

Some tests applied in the screening are expected to be applicable as clinical pre- and post-tests as well; e.g., binocular visual acuity or stereo acuity. For specific vergence measurements the clinical tests can include: (1) fusional reserves, which denotes the amount of vergence, both diverged and converged, that can be endured before blurring or double vision occurs; (2) relative vergence, which provides information on vergence facility, e.g., the effect of exhaustion by prism flippers on fusion; and (3) fixation disparity, which relates visual stress to prism strength necessary to redirect perceived objects to corresponding parts of the retina.[31,55,56,75] Specific accommodation measurements can include: (1) accommodation amplitude, which denotes the maximal range of accommodation, e.g., push-up method of Donders; (2) relative accommodation, which provides information on the accommodation facility, e.g., jump accommodation with lens flippers; and (3) accommodation accuracy, which describes the difference between the accommodation necessary for a certain viewing distance and the measured accommodation.[31,55,56]

*Brain Activity Measures*

All sensory and high-level cognitive information is processed in the brain. As such, the neuronal activity in the brain also reflects visual fatigue as a consequence of viewing stereoscopic content. Brain activity measurements provide information on changes in brain activity as a result of simultaneous behavior changes and provide knowledge that extends from better understanding of perceptual and cognitive processes to characterization of a variety of pathologies including specific visual disabilities.[83,84] To overcome limitations and exploit advantages in sensitivity and specificity, high-quality spatial information [e.g., functional magnetic resonance imaging (fMRI)] can be combined with high-quality temporal resolutions [e.g., magneto encephalography (MEG) and electroencephalography (EEG)][85,86].

Most brain activity research related to depth perception concentrates on fundamental issues, such as identifying the exact pathways for binocular vision.[87–89] There is little work done on depth perception of stereoscopic content on 3D displays and relating aspects such as visual fatigue. This may be attributed to the fact that visual fatigue refers to multiple conflicting interactive visual modalities or that other evaluation tools are more practical. The few studies that have applied brain activity measurements though revealed interesting results.

Emoto et al.[31] used EEG to measure the visually evoked cortical potentials; i.e., an evoked potential by sensory stimulation of the visual field. Visually evoked cortical potentials reflect fatigue of the interrelated extraocular muscles, intraocular muscles, and central nerve of the brain. The P100 latency (positive component at approximately 100 ms latency) of the visually evoked cortical potential was used as a fatigue index. Delays of the P100 latency were found between pre- and post-exposure to different parallax settings. For temporally changing parallax, the delays were significant. Furthermore, as stated before, high correlations were found between P100 latencies and relative vergence limits. Li et al.[90] used background EEG and event related potentials to measure visual fatigue. The frequency spectrum of the background EEG signals is known to indicate the state of stress; i.e., higher frequencies starting at $\pm 12$ Hz denote stressful situations. Though stressful situations also delay the P300 latency of the event related potentials, they found that the delay was much stronger for the P700 latency. Results revealed that the power of the spectrum of the background EEG as well as the delay in the P700 latency depended on binocular parallax and presentation time, which was confirmed by subjective assessments. Hence, delays in the transmission of visual information measured with EEG seems to be an appropriate measure for visual fatigue.

Hagura et al.[91] performed a preliminary study to apply fMRI in combination with MEG as a measurement tool to detect visual fatigue during 3D experiments. This combination allows dipole data acquired by the MEG to be superimposed on a 3D model composed by the fMRI. As a result of viewing random dot stereograms, brain activity in the back left side of the brain was revealed. The isocontour maps of the dipole activity differed for different viewing periods. However, the isocontour maps were not clear enough to locate and identify exact activated locations. Hence, it seems that further investigation is required to apply MEG and fMRI as brain activity measurements for visual fatigue.

## DISCUSSION

Visual fatigue and visual discomfort are related to many different aspects of the human visual system, thus remain somewhat ambiguous concepts when used in a general sense. However, for the purpose of our current review, we define visual fatigue as physiological strain or stress resulting from excessive exertion of the visual system. It is a state that can be objectively quantified in theory. Visual comfort is its subjective counterpart. In order to distinguish clinically significant visual fatigue from unproblematic, functional adaptations of the visual system, we need to establish relationships with subjective indicators of visual discomfort and monitor potential damage of the visual system as a result of prolonged viewing. 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, in most cases concerns measurements with optometric devices on the visual system that are generally costly, time-consuming, and are usually conducted with only small numbers of participants, making the results less reliable. Furthermore, optometric devices that measure all the modalities of the ocular triad are not yet commercially available and should be custom built. Brain activity measurements such as EEG, MEG, and fMRI, receiving increasing attention in the last decade, provide an interesting framework for cognitive neuroscience and a promising tool for researching the fundamental nature of asthenopia, yet remain impractical and for most research facilities too costly for psychophysical experiments. Nonetheless, EEG measurements provided promising results in detecting visual fatigue. Clinical measurement methods on the other hand, are relatively cheap, concise, noninterventional, quantitative with a high sensitivity and specificity, and applicable to a large group of participants. More research, however, is needed to determine which specific clinical methods can be used to quantify the degree of visual fatigue from stereoscopic displays. Multiple objective indicators are argued for the evaluation of visual fatigue since a single underlying factor, e.g., vergence insufficiency, can stimulate different anatomical locations and result in different sensations. Combined measurements of EEG and clinical methods provide an appropriate framework to measure visual fatigue, since latencies in EEGs and relative vergence limits correlate.

Ideally, we would like to arrive at a general and easily applicable indicator of visual fatigue and visual discomfort. When a robust relationship is established between the visual discomfort and the visual fatigue indicator, one might be used to substitute the other, where appropriate. This would allow the study of large groups of participants using easily applicable visual discomfort 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 their developing visual system has 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 a zone of comfortable viewing, Percival's area of comfort seems not to be appropriate for stereoscopic displays. This area is determined by the use of prisms, which create stereoscopic content that perceptually differs from content on stereoscopic displays. We support the use of a maximum screen disparity that corresponds to a retinal disparity of 1° as a limit for a zone of comfortable viewing. This still allows satisfactory depth perception for 3D TV applications, though no 3D display can display the amount of depth at large viewing distances that results from 1° of disparity. It appears to prevent the "classical" causes of visual discomfort, i.e., excessive screen disparity and accommodation-vergence conflict, from being perceptually annoying. Fusion is possible and blur is not perceived; hence, stereoscopic viewing should be comfortable within this limit. Beyond this limit clear and single binocular vision is still possible, yet not comfortable, up to a point at which blur and double vision are perceived. Hence, peak screen disparities may be induced in stereoscopic movies or games to increase the 3D experience, but not too often or for extended periods. With certain stereoscopic image content, however, visual discomfort may still occur within this limit, and we believe three factors to be the most pertinent ones. The first factor is temporally changing demand of the accommodation-vergence linkage, which potentially can be caused by fast motion in spatial and depth direction and is expected to become more severe with prolonged viewing and at short viewing distances. The second factor concerns 3D artifacts, resulting from insufficient depth information in the incoming data signal, yielding spatial and temporal inconsistencies. Such artifacts have not been subjected to much research yet, though inconsistencies, such as conflicts between depth cues and geometrical distortions have already proved to cause annoyance and visual discomfort. The third factor concerns unnatural 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 difficulty in fusion, and it can strengthen the accommodation stimulus, thereby causing conflicts between accommodation and vergence. A surplus of blur resulting from crosstalk, 2D-to-3D conversion, and artificially induced DOF causes annoyance, visual discomfort, and can result in depth cue conflicts as well.

## CONCLUSION

In this article 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 "1° 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) temporally changing demand of accommodation-vergence linkage, e.g., by fast motion in depth; (2) 3D artifacts resulting from insufficient depth information in the incoming data signal yielding spatial and temporal inconsistencies; and (3) unnatural 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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