

Causes of discomfort in stereoscopic content: a review

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Abstract

This paper reviews the causes of discomfort in viewing stereoscopic content. These include objective factors, such as misaligned images, as well as subjective factors, such as excessive disparity. Different approaches to the measurement of visual discomfort are also reviewed, in relation to the underlying physiological and psychophysical processes. The importance of understanding these issues, in the context of new display technologies, is emphasized.

1 Introduction

The availability of stereoscopic displays and content has increased greatly, during the last ten years. In addition to the many new films produced in 3D, there is a market for re-releases of older movies adapted to 3D, and a strong push by TV manufacturers toward stereoscopic viewing. There are indications, however, that there has been a decline in popularity of 3D movies in the last two to three years, and many attribute this decline to complaints of discomfort associated with viewing 3D content.

A 2013 study on 433 subjects estimated that 14% of people suffer from some discomfort symptoms, with additional 8% reporting discomfort related to wearing the special equipment needed, such as 3D glasses. Symptoms were reported to be mainly headache and eyestrain [131]. Another study from the same year on 524 subjects reported that more than half of the viewers suffer from some symptoms [144]. It seems plausible that this discomfort may play a role in the declining popularity of stereoscopic films.

Results like these (obtained on smaller sam-

ples) were known for many years [79] and have led to research on the causes of discomfort. This research has flourished in the past few years, with a number of papers which summarise the main findings [156, 81, 53, 149, 8, 159, 96]. A number of guidelines have appeared for cinematographers [103, 191], and quality assessment of stereo images and videos became important, though typically with a stronger focus on image quality than viewer discomfort [173].

This report presents a new and comprehensive overview of the findings in this field. We feel that such a review is necessary for several reasons. First, it is a very active field, and many new facts have surfaced in recent years. More than half of the results presented here are from the last five years, and a third were published since 2013. These recent advances are not covered by previous reviews. Second, there has been a recent push into obtaining physiological insight by using objective measurement techniques such as brain scans. We feel that this important part of the equation has not been adequately addressed by previous reviews of discomfort literature. A recent review on objective measurements dealt with effects of stereoscopic and 3D viewing in general and did not specifically focus on comfort or fatigue [120]. To our knowledge, this is the first work to attempt to include this data into a wider discussion of discomfort. Finally, there is a strong push toward new, non-traditional displays, such as head-mounted displays (HMDs) for virtual reality, mobile devices and smart glasses [140]. Affordable consumer HMDs are set to arrive in 2016, and the immersive nature of VR applications could lead to strong visual fatigue. We discuss specific issues related to these new technologies.

This paper is structured as follows. In Sec. 2 we give a brief overview of the visual system, and discuss how stereoscopic viewing can stress it in unusual ways. In Sec. 3 we discuss subjective and objective measurement techniques used to assess visual discomfort. In Sec. 4 we summarise the type of content strongly associated with discomfort, most of which was obtained through numerous subjective studies. In Sec. 5 we summarise the current understanding of the physiological basis of discomfort, based on objective measurements. Sec. 6 discusses considerations specific to emerging technologies such as HMDs, followed by a discussion in Sec. 7 and a conclusion.

2 Visual system and stereoscopy

Our visual system evolved to process natural scenes. In this section, we briefly introduce the human visual system and point out how stereoscopic video differs from natural viewing and can thus provoke an unnatural response. Then in later sections, content related to discomfort and measurements of physiological factors will be analysed in more detail.

2.1 Eye movements and geometry

The basis of stereo vision is the ability of our visual system to fuse the left and right views into a single cyclopean view of the scene. The apparent displacement of objects when viewed from two positions is called *parallax* and it gives rise to *retinal disparity*, the difference in location of the object's projections on the left and right retina.

Opposite eye rotations are called vergence, and one often speaks of convergence (eyes rotating inward) or divergence (eyes rotating outward). In natural viewing, the eyes converge on an object of interest, so that the object's retinal projections have near-zero retinal disparity. The locus of zero disparity is called the horopter. Within a small region around the horopter, where disparity is small, the visual system perceives a single object. This area is called Panum's fusional area [10], and measurements suggest that disparities of up to 0.5 degrees can be fused [183], though the specific value depends on the location on the retina and is closer to

0.1 deg around the fovea [81]. In practice, hard limits are difficult to measure because disparity sensitivity is tied to luminance and contrast [33], as well as spatial frequency content [135].

In stereoscopic viewing, other types of eye movement may result from incorrect camera geometry. For example, vertical offset between the left and right views causes vertical vergence [51]. This is discussed in more detail in Sec. 4.

2.2 Accommodation and vergence

The process of vergence is related to accommodation, the process by which the eyes bring the converged object into sharp focus. Accommodation error must be within $\pm 0.25\text{D}$ (diopters) for the object to appear sharp [49]; at the same time, accommodation results in blurring of objects which are difficult to fuse. Accommodation and vergence are known to be tightly coupled [37, 101, 133] and can be modelled by a dual-parallel feedback-control system [81], the result of which is that both vergence and accommodation are faster when coupled [31]. Moreover, vergence speed is dependent on initial position [4], so small depth adjustments are faster.

The zone in which an object is both sharp and has low disparity is termed the Zone of Clear Single Binocular Vision (ZCSBV) [40]. It measures maximal decoupling while maintaining a clear, single, binocular percept. ZCSBV does not guarantee comfortable viewing. Percival's zone of comfort [125] is defined as the middle third of ZCSBV, and the alternative Sheard's zone [137] is a bit better predictor for exophores [138]. These measures were developed for natural viewing, and correlate well with stereoscopic viewing for near distances, but not for far distances [139].

Stereo 3D breaks the coupling between vergence and accommodation because the eyes keep a sharp focus on the screen depth, while vergence is varied to process varying disparities. Shibata's Zone of Comfort [139] was specifically developed to address this issue. Even within the comfortable zone, problems can arise if there is much variation in screen disparity [113, 114]. More discomfort is felt when the conflict changes rapidly [9, 76].

The effects of the vergence-accommodation conflict are numerous. An experiment by Hoff-

man et al. showed that it significantly affects discomfort and degrades depth perception [49]. It increases the time required for fusion [169, 2, 71], which affects fast-moving objects and cuts between scenes. After an hour of watching stereoscopic material, there is a measurable decline in accommodation response suggesting fatigue [182]. Accommodation response is normal if the object in focus is within the depth of field [48], otherwise it seeks a more comfortable and less stressful state [118].

This topic is subject to active research. A recent study [141] indicates that the conflict occurs only with near displays and is not a factor for many viewing scenarios. Another study found the effect to be worse on small displays [28], which agrees with this finding.

2.3 Depth cues

The visual system uses a number of different cues to determine depth. They include blur, shading, perspective, disparity, haze and motion [119]. In addition to these bottom-up cues, top-down effects also influence depth perception [21, 171]. While ambient illumination is not important for depth perception [127], high-contrast lighting helps to enhance the apparent depth of a scene [10].

There is no unified model of how the depth cues are combined [52] but the process is often modelled in the Maximum Likelihood framework [38]. The visual system can resolve conflicting cues [146], but when there is strong conflict, rivalry dominates [47]. In terms of discomfort, it has been shown that cue combination using Minkowski summation is a good predictor for overall levels of visual discomfort. The overall level of perceived discomfort is determined by the most significant discomfort factor in a winner-takes-all manner [87].

Disparity is one of the most important cues, and forms the basis of stereoscopic vision. Discrimination thresholds are higher for larger corrugations [52] and larger disparities [15]. Disparity sensitivity is similar to the contrast sensitivity function [19]. Depth is dominated by distribution of disparity contrasts, strong at discontinuities and weaker at ramps [20], which might explain the apparent “flatness” of stereoscopic 3D.

Stereoscopic 3D can provide inconsistent depth cues. In natural viewing, focus blur is an important cue, but it is absent in stereoscopic 3D. This also results in a lack of blur gradient along ramps and smooth depth transitions, which adds to the perceived flatness of the scene [169]. The parallax due to head movement is completely absent, though on-screen motion still provides a strong dynamic parallax. Other incorrect cues include fixed accommodation, and wrong sizes of observed objects, leading to the “puppet theatre effect”.

2.4 Visual cortex

The primary visual cortex V1 receives retinal images via the Lateral Geniculate Nucleus and processes them through a combination of simple, complex and end-stopped cells, for which efficient computational models exist [151]. Even at this early stage, the left and right stimuli are processed together and cells associated with the same retinal position in left and right views are located close to each other in the cortex, hinting at stereo disparity processing early in visual cortex [110]. From here, coarse disparity is associated with the “dorsal” pathway responsible for localisation and spatial layout, via cortical areas V2, V3 and MT [121], while fine disparities aid shape and object recognition in the “ventral” pathway, via V2, V4, and IT. Numerous computational models for cortical disparity calculation have been proposed, including phase-based stereo, disparity energy [150], and sparse matching of end-stopped cell responses [151], but disparity processing is still subject to intensive research.

Top-down influence on depth perception has long been established [21, 171], which hints at the involvement of higher cognitive processes in depth perception. Mental fatigue in trying to resolve conflicting cues is a possible cause of discomfort.

2.5 Eye fixations and attention

Our visual system processes the scene sequentially through a sequence of saccades, preferring “salient” parts of the image. Depth is known to strongly affect the salience of image regions [99], leading to a number of salience measures

which incorporate depth [129, 163]. There is a correlation between salience and discomfort [29, 62], and computational models of discomfort perform better once salience is taken into account [142, 67, 162].

3 Techniques for measuring discomfort

In order to tackle discomfort, we must first be able to measure it. While there is a good review of measurement techniques related to stereoscopic vision in general by Park and Mun [120], it does not focus on discomfort specifically. Similarly, literature reviews which focus on Quality Assessment of stereoscopic video are primarily concerned with the perceived quality of the video and viewing preference, of which discomfort is only a factor [104, 147]. In this chapter, we quickly summarise the types of measurements used to assess visual discomfort before we discuss the major findings in the following sections.

There are two major types of measurement: subjective measurement, which involves asking the viewers to assess the amount of discomfort by filling out questionnaires or moving sliders; and objective measurements, which observe the body's response to stereoscopic video through eye trackers and brain scans. Subjective measurement is crucial for determining which content and viewing conditions cause discomfort and detecting that discomfort is present. Objective measurement can help us understand the underlying physical processes which lead to it by comparing the responses during normal viewing and uncomfortable viewing. Lambooij stresses the difference between discomfort, which is subjective, and fatigue, which is objective and measurable [81].

Measurement is difficult because, people are more likely to disagree about quality of depth than the quality of flat images [26], so results tend to be less consistent. Discomfort also depends on stereoacuity (more discomfort for better stereoacuity) [77]. It is not clear how discomfort is affected by age: some studies found no big difference between children and adults [126, 187] but other studies suggest that this only holds for large disparities and medium ambient illumination [167]. Yang et al. found that younger

people are disproportionately affected [180, 108]. Women are found to be more strongly affected than men [187, 108]. Also, a strong hereditary influence has been suggested in a recent study [86]. All this suggests that more personalised media will be necessary in the future.

3.1 Subjective measurement

The only certain way to know if someone is comfortable is to ask them. Subjective measurement also has the benefit of easily obtaining many sample points (some studies used hundreds of subjects). The problems involve the inconsistency (questionnaires are subjective by their very nature) and fatigue associated with long tests. Subjective evaluation is important because it allows us to identify problematic content, and most insights presented in the next section were obtained from user studies. A number of protocols have been applied to discomfort measurement, such as the Binocular Just Noticeable Difference model to calculate distortion visibility threshold [43].

The most important method applied to discomfort measurement is probably the ITU recommendation BT.500-10, which measures a wide range of image impairments on a scale from "imperceptible" to "very annoying" [60]. For example, it has been applied for measuring the effect of crosstalk [11], but it was originally designed to measure image quality, not comfort. Even when it is modified by researchers, this recommendation is still important because it defines many test conditions which can help to improve consistency between tests. The ATSC suggested using a single Likert scale ranging from "very comfortable" to "very uncomfortable" [1]. Hoffman et al. used a combination of five-point Likert scales covering aspects such as how tired the eyes feel and how clear the vision [49]. The Convergence Insufficiency Symptom Survey (CISS) by Lambooij et al. addressed different aspects of discomfort, such as double vision and sleepiness [81], and Yang et al. added psychological factors such as impaired memory, disorientation, dizziness and vertigo [179]. The Stereoscopic Discomfort Scale (SDS) of Bracco et al. combines previous measures and extends them with new ones in order to create a more complete standard [18]. Unfortunately, none of these scales has been

widely adopted, and many are still based on the ITU scale, making comparisons difficult.

Questionnaires may be completed after a video clip has been viewed. In order to obtain near real-time measurements, researchers have turned to continuous response measurement techniques [14]. ITU BT.500 includes the Single Stimulus Continuous Quality Evaluation (SSCQE) protocol first introduced by Hamberg and De Ridder [45] which has been applied to stereo discomfort measurements, e.g. [82, 182, 58]. In Quality Assessment, a number of metrics have been developed to predict discomfort [161]

3.2 Objective measurement

Objective measurements have the advantage that they can be automated, and tell us more about physiological causes of discomfort. However, they must correlate well with subjective results in order to be useful, and this is often difficult.

A wide variety of physiological measurement techniques exist, but only few have successfully applied to predicting discomfort. It is known that ECG can measure cognitive load [42], which is one measure of strain and fatigue. Brain responses can be measured via EEG and fMRI scans, and both have been shown to correlate with visual fatigue. Finally, ophthalmological measurements such as eye movement, pupil size and vergence have been used to measure these factors directly and determine their correlation with visual discomfort. A summary of related findings is given in Sec. 5.

4 Content associated with discomfort

It has been suggested that visual discomfort is caused by the instability of the perceived world [55]. Stereo 3D is an imperfect simulation of the real world, and as discussed in Section 2, this can cause unnatural strain on different parts of our visual system. Therefore, it follows that content has a large influence on perceived discomfort: the type of content which forces the visual system to act in an unnatural way is more likely to cause discomfort. It is important to note here that discomfort and perceived image quality are

not the same thing. While there is much research on quality assessment of stereoscopic images and video, the perceived image quality is not necessarily a guarantee that extended viewing will be comfortable.

A number of different surveys performed over the years have identified the types of content most likely to cause discomfort. They are incorrect viewing geometry [12], vertical disparity [79], excessive horizontal disparity and rapidly moving objects [182, 82], crosstalk [79, 165], unnatural blur [118, 79], window violations [98], fast motion in depth [124, 82, 83], and image distortion from incorrect pre-processing [174]. In the following, we discuss these factors in more detail and attempt to quantify them.

4.1 Incorrect viewing geometry

The human visual system evolved to view natural scenes, and is optimised for this particular constrained viewing geometry. When artificially created stereoscopic images are presented to the eyes, these constraints are violated, leading to additional stress on the visual system [12]. One of the first analyses of image distortion in stereo viewing was given by Woods [174].

In natural viewing, the distance between the eyes (interaxial distance) is fixed, but the distance between two cameras in a stereo configuration can vary. Cinematographers often modify the separation of the cameras for each scene separately to adjust the amount of disparity in a shot [50, 107]. Surprisingly, viewers do not seem to be very sensitive to this; they ignore motion and stereo cues in favour of a fictional stable world [41].

The primary depth cue in stereoscopic content is horizontal disparity – the horizontal offset of an object in one view compared to the other. The fixed position of the eyes ensures that horizontal disparity dominates regardless of the position of the head, and our visual system is particularly good at processing horizontal disparities. When two cameras in a stereo configuration are misaligned, the left and right images are no longer vertically aligned and this has been identified as a major factor in discomfort [79]. The eyes adjust to this situation through vertical vergence where the two eyes rotate vertically in opposite directions [3]. This movement is not natu-

ral and eventually leads to fatigue [51]. Acceptable levels of vertical disparity are considered to be about 15 arcmin, corresponding to a torsional disparity of about 30 deg of relative orientation [155]. Displays which show left and right images on alternating rows provoke the same response, but this effect is considered too slight to cause eyestrain [10]. Vertical misalignment can be easily fixed during acquisition, but it also surfaces with “good” videos. If the head is not kept vertical, a rotation of the two views will result on most displays [68]. This means that simply tilting the head in natural viewing can lead to discomfort.

A more complex situation occurs when the two images are not simply offset, but shot from a different perspective, as in an toe-in configuration. This also causes vertical disparities [102, 174, 79, 168], but causes additional problems. Such content can also be visually confusing, because of implicit cues about camera alignment [97, 115]. Toe-in camera configuration gained popularity in part because it was thought that it reduces the need for cropping. Material captured by cameras in a parallel configuration will inevitably have parts in each image which are not visible in the other. If an object appears in these regions, this leads to window violations [98], which are a major cause of discomfort [190]. Because of these factors, toe-in filming is discouraged today in favour of parallel cameras followed by cropping. [10].

Incorrect viewing geometry puts extreme stress on the visual system. Luckily, many of the worst aspects can be eliminated if well-calibrated and properly aligned cameras are used during acquisition. The problem with head rotation during viewing is, unfortunately, much more difficult to solve without HMDs.

4.2 Crosstalk

Crosstalk (or ‘leakage’) is the process by which one image is combined with another during playback. The resulting effect, where objects are seen in double, is called “ghosting”. Huang distinguishes between system crosstalk (related to the device) and viewing crosstalk (related to the content) [54]. This effect is entirely unnatural and completely caused by imperfect technology and as such, it is reported as one of the most annoy-

ing factors in stereo 3D [79, 165].

The wide range of causes of crosstalk means that there is no unified solution. It depends on the specific display, specific shutter glasses (if used) and the viewing angle [186] and due to the wide range of available display equipment, reported results are not always consistent. Passive glasses are traditionally considered more prone to crosstalk (especially colour filter-based anaglyph glasses), and there are systems which claim that shutter glasses eliminate ghosting completely by some measures [25]. On the other hand, a study from 2013 claims that crosstalk is lower on passive displays than on active displays [185]. Yet another study found no major difference between active and passive stereo [164]. It is widely accepted, however, that crosstalk contributes to discomfort and can be removed by technological means.

It has been claimed that around 20% crosstalk is considered acceptable with mirror-type displays [163], but this seems high for normal stereo content. One study finds that 15% is considered annoying [136], while another one recommends less than 10% [112]. Quality impairment is sufficient to affect depth perception with as little as 4% [154], but there is no proof that such levels of crosstalk cause discomfort. Annoyance due to crosstalk increases with increasing disparity [164], increasing camera base distance [136, 176] contrast [164], and scene content [176].

Crosstalk negatively affects depth perception [154, 153] which can cause additional strain. Perceptual crosstalk tests show that interocular crosstalk is a function of spatial frequency [59].

Where present, crosstalk can be masked by perceived motion blur, especially at low binocular parallax, which limits the crosstalk-induced image quality degradation [166]. It has also been argued that the blurring caused by crosstalk can reduce the vergence-accommodation conflict so small amounts of crosstalk can be beneficial in practice [81], but there are more effective depth-of-field methods for dealing with this problem.

4.3 Excessive Disparity

Unlike vertical disparity, our visual system is well-equipped to deal with large horizontal disparities. But even here, there are limits to what the visual system is capable of fusing, and the

failure to fuse can be very uncomfortable if it persists over long periods of time. It is easy to perform acquisition in a way which results in excessive disparities, so care is needed. Experiments have shown that there is a comfortable viewing range [175, 63] which limits the allowed horizontal disparities. In addition to absolute disparity, the relation to object is also important, as smaller stimulus width causes more strain [89], as does a large disparity between the foreground and the background [71].

In cinematography, there are guidelines. Mendiburu cites the 3% rule [103]. Lambooij argues for one degree of screen disparity [81]. Williams gives the maximum disparity as 25% (in front) or 60% (behind) of the viewing distance [172]. Excessive disparities are closely tied to the accommodation-vergence conflict. Shiba et al. determined that the comfortable limits are 2-3% of the screen width for crossed (in front) and 1-2% for uncrossed (behind) disparities [139]. While differently stated, all of these measures are quite comparable and serve to illustrate that the range of depths in stereoscopic 3D must be tightly controlled to a sub-volume centred around the screen depth. This severely limits the range of disparities allowed for a comfortable viewing experience.

The difficulty of keeping disparities within this range during acquisition has spawned a number of computer algorithms capable of automatically adjusting the disparity range of existing stereo content [84, 178, 128, 64, 143, 116].

4.4 Blur

Blur plays an important role in depth perception [188], and it is also crucial in reducing discomfort. Unnatural blur is often cited as a cause of viewing discomfort in stereo images [118, 79]. However, it has been recently argued that artificial blur itself does not induce discomfort when applied to a scene, so it is the inconsistency with the accommodation process that is the likely cause [117]. Wopking proposed that depth of field helps discomfort [175], which was later proved by Blohm [16], who showed that test subjects prefer images where only a subvolume corresponding to a limited range of depths is in sharp focus. The rest of the scene is blurred, and corresponding disparities masked, resulting

in a limited disparity range as described in the previous section.

In natural viewing, the visual system keeps the object of interest in sharp focus through the process of accommodation to this specific distance. Since the vergence and accommodation mechanisms are coupled (see Sec. 2), the object in focus should have near-zero disparity. Objects which are in front or behind this plane are blurred. The benefit of this process is that objects exhibiting large disparities are blurred more strongly, and our visual system does not attempt to fuse them. Thus it is the absence of accurate blur in most stereoscopic video that contributes to discomfort by overloading the visual system.

An additional problem is caused by the absence of blur gradient along depth gradients. Disparity as a cue is strongest at sharp boundaries, and the absence of blur-based cues results in an impression that all objects in the scene are flattened. The visual system works hard to try to resolve the conflict with the high-level expectation, which can lead to fatigue.

Blur is a difficult aspect to address. Since stereoscopic video is presented at a fixed distance, the eyes will naturally accommodate to this distance, thus losing blur as an important depth cue. Systems based on eye tracking [35] and selective blurring [90] have either failed to improve viewing comfort, or have had to sacrifice image quality.

4.5 Motion in depth

It is not clear that movement in stereoscopic films is uncomfortable *per se* [95], but there are particular types of movement associated with discomfort. For example, Yano et al. report that in-plane motion within the zone of comfort does not lead to more fatigue than 2D viewing [181].

Most authors single out motion in depth as particularly uncomfortable, as first studied in detail by Speranza [145]. There seems to be complete agreement among researchers on this point [124, 82, 83, 98]. The worst culprit is motion between positive and negative disparity [145, 98]. According to much research, slow motion in depth is more comfortable than fast motion in depth, which should be avoided [124, 82, 83]. But the evidence here does not seem to be conclusive. Recent research by Hartle et al. ex-

amined viewer preferences for different types of camera movement and found that there is some preference for faster movement [46], specifically for the movement-in-depth case. They conclude that viewer preferences are complex and do not necessarily exhibit direct relation with an individual cause.

In natural viewing, an observer will analyse the scene by sequentially focussing on different scene objects, which requires oculomotor adaptation to corresponding depths. The speed of vergence depends on the disparity jump [130], but the coupling between vergence and accommodation is optimised for natural viewing. From the earlier discussion of the vergence-accommodation conflict, it was seen that the eyes' adjustment to depth is slower for stereo 3D than in natural viewing [31, 169, 2, 49], which affects any change in observed depth. Recent results provide evidence that dividing attention between multiple salient objects is a cause of discomfort [188]. This has also been shown for movement consisting of steps in depth [181] and depth jumps [98]. This effect severely constrains the make-up of stereoscopic video. In addition to minimising the depth range in a scene, which was discussed in Sec. 4.3, it also means that sharp cuts are a potential cause of discomfort and that content creators should ensure that such cuts do not result in sharp changes in disparity. A qualitative study of combinations of factors found that frequency and abruptness of disparity change were the strongest cause of discomfort [74].

Other types of motion can also lead to problems. It has been noted that rapidly moving objects have an effect on viewing comfort [82], and research showed that relative disparity [93] and velocity [88] are main factors for visual discomfort in the case of planar motion. Similar findings were reported by Tam [149] and by Du, who proposed a comfort metric which incorporated 3D motion [34]. All of this suggests that stereoscopic videos should be more constrained, not only in depth range, but also in the speed of movement. The popularity of fast action movies with quick cuts, many of which are shown in 3D, seems to present a problem for comfortable viewing.

4.6 Visual tolerance

After outlining all the content which causes or exacerbates viewing discomfort, we are happy to report that there is also content which is not problematic. A 2015 study on 854 subjects showed that seating position (in a cinema) did not matter. It also found that more recent films caused less discomfort, suggesting that acquisition is improving in line with the findings and best practices outlined in this chapter [187].

While difference in zoom between the left and right views can cause discomfort by introducing vertical disparities and create the appearance that the scene is slanted and cause problems [115], it was found that difference in spatial resolution is not crucial [146], and neither are differences in interocular luminance [17]. Since this is common in natural viewing (e.g. with people who are near-sighted on one eye only), our visual system may have evolved to deal with such situations.

5 Physiological factors of discomfort

It has been suggested that ECG measurements can indicate an overload of the autonomic nervous system [120], and a recent study found a correlation between ECG readings and visual discomfort caused by stereoscopic viewing [69]. Not all studies found such a correlation, for example no difference was found in ECG LF/HF ratio [109]. Most of the objective measurements have concentrated on eye responses and brain scans.

5.1 Ophthalmological factors

It has been argued that oculomotor factors are predominant in visual symptoms and there is some correlation between discomfort and microsaccadic movements [160]. Blinking is correlated with eyestrain [85, 70], but it is not always a good predictor of discomfort [94]. Researchers have, however succeeded in mapping eye blinks to subjective discomfort scores [29]. Another study using EOG [184] detected more saccades and blinks for stereoscopic 3D than for 2D material, which could be one of the causes of fatigue. More recently, several studies showed

that a statistical analysis of eye tracking data can predict discomfort [57, 30]. Kim and Lee found that visual attention is strongly affected by visual fatigue and they incorporated this insight into their Transition of Visual Attention model [75].

Care is needed, because while the link between blinking duration and number of saccades with visual fatigue has been established, measurements of the pupil diameter and fixations are not always precise enough and are highly dependent on content [56]. It is likely that technological improvement will resolve these problems [120]. It has been suggested that reading speed can be a useful proxy for fatigue, as it decreases as a result of visual fatigue [80].

Additional information has been obtained through direct measurements of vergence and accommodation [111]. It has been observed by Ukai and Kato that vergence and accommodation are impaired when observing stereoscopic 3D [157]. After an initial adjustment of accommodation to correspond with the change in vergence, accommodation returns to the screen surface, causing an oscillatory behaviour in both accommodation and vergence. Cho et al. showed that accommodation depends on the amount of blur [27], and subsequent research confirmed that low-pass filtering influences accommodation response [152]. Therefore, selective blurring may help reduce discomfort. Several studies found that the vergence-accommodation mechanism is impaired after prolonged viewing of stereoscopic material [134, 132], in particular the natural accomodative response is slowed down [61, 148].

Kim et al. directly measured fusion time and found that discomfort depends on the parallax difference between foreground and background [71]. A wide range of ophthalmological measurements by Wee et al. included near point of accommodation (NPA) and convergence (NPC), amplitude of fusional convergence and divergence, tear break-up time and temperature of ocular surface, and angle of phoric deviation [170]. They found that accommodation and binocular vergence are the predominant factors of discomfort.

5.2 Neural factors

While there have been recorded attempts of using different types of technologies including MEG [44], most research has concentrated on real-time (but less precise) EEG measurements and more detailed (but slower) MRI imaging techniques.

5.2.1 EEG

Cortical measurements of 3D-induced visual fatigue date back at least to Yamazaki et al. [177], who found P100 latency to be a good predictor of fatigue. P100 relates to event-related potentials (ERP) and refers to a cortical response to an event after an approximate 100ms delay. The P100 latency was shown to increase in visual evoked cortical potentials in the left (LO), right (RO) and middle (MO) parts of the occipital lobe, and the vertex (Cz) [36]. These effects disappeared after a rest. Similarly, an increase in P300 and P700 was also observed after prolonged stereoscopic viewing [92]. Significant reduction in P600 potentials and increase in P600 latencies was observed by Mun et al. [106]. They additionally measured steady-state visually evoked potentials (SSVEP), which are more commonly related to low-level processing. Significant reduction in attend/ignore ratios was obtained after stereoscopic viewing in the parietal area P4 and occipital area O2. An uncomfortable stereoscopy correlates with a weaker negative component and a delayed positive component in ERP [39]. Interestingly, passive polarised displays do not seem to affect ERP [5, 6], but the authors note that this could be due to the simple 3D stimuli used in the test.

Background EEG readings can also serve as a measure of fatigue [92]. Chen et al. found that the gravity frequency of the EEG power spectrum and power spectral entropy decrease after prolonged periods of watching 3D TV and showed that these measurements can act as a predictor of fatigue [24]. Both gravity frequency and power spectral entropy are decreased greatly on frontal and temporal, and especially in the prefrontal region after continued 3D viewing, while the effect on gravity was not significant on parietal and central areas [23].

Models based on alpha, beta and theta activi-

ties have been proposed in the literature. Power of high-frequency components which are associated with stress, including the beta band, increases during 3D viewing [92, 78]. Frey et al. measured a power decrease in the alpha band and increases in theta and beta bands in the parietal area Pz when viewing non-comfortable content [39]. However, beta activity seems to reduce with the onset of fatigue. Zou et al. found a significant increase in alpha and a reduction in beta activity after prolonged stereoscopic viewing and the onset of fatigue, and suggest that alpha may be the most promising index for measuring fatigue [192]. Zhao et al. developed a multi-variate regression model of fatigue based on a combination of different frequency bands [189].

5.2.2 MRI

It is known that activity in the occipital lobe (notably V3) and parietal lobe (notably MT) is very sensitive to disparity and correlated with fatigue [7]. A large fMRI study by Chen et al. found that processing information at different depth significantly affects brain function. After prolonged 3D viewing, there were changes in brain areas BA17, BA18 and BA19 (the latter contains V3,V4, and MT), which are related to visual search, as well as in the Frontal Eye Field in B8, which is associated with uncertainty and expectation [22]. Kim et al. also found changes in the FEF for stimuli outside of the comfort zone [73].

A set of experiments by Jung et al. examined the brain's response to excessive disparities which are a common cause of reported discomfort. They found that the right middle frontal gyrus (MFG), the right inferior frontal gyrus (IFG), the right intraparietal lobule (IPL), the right middle temporal gyrus (MTG), and the bilateral cuneus were significantly activated during the processing of excessive disparities, compared to those of small disparities [65, 66]. They conclude that discomfort due to excessive disparities involves both sensory and motor phenomena. In a comparison, between high-fatigue and low-fatigue groups, the high-fatigue group showed more activation at the intraparietal sulcus (IPS) than the low-fatigue group, when viewing an excessive disparity stimulus [72], hinting at the increased strain on visual attention and eye movement control.

6 Considerations for emerging technologies

Increased popularity of head-mounted displays (HMDs) and mobile devices brought some specific issues related to these devices. Ukai and Howarth note problems with the technology in early HMDs which caused fatigue and eye strain [156] Stereoscopic HMDs require a strict alignment of axes, and any small errors will increase symptoms related to geometric misalignment. They also tend to increase the feeling of visually-induced motion sickness (VIMS) due to the inconsistency of visual and other vestibular cues (such as gravity and acceleration) [158]. This problem is alleviated the the latest HMDs which incorporate high quality head-tracking, but latency has to be very low. Even so, there are still conflicts with the vestibular system as a result of constrained peripheral vision [105].

An early evaluation of HMDs did not find a difference from viewing stereoscopic images on a desktop computer [123], but more recent studies certainly found important factors. For one, the screen is extremely close to the eye causing a strong accommodative response, yet the eyes may converge onto a point in a distance. Hence, nearby displays have been shown to be less comfortable [141]. Since an HMD must be close to the eye by design, the only viable solution may be to exploit the effect that blur can have on accommodation [27]. Early eye-tracking prototypes implementing this on HMDs exist, but are still in early stages and do not improve comfort at the moment [35]. In a comprehensive review of user factors affecting HMD users, Patterson et al. recommend a fixed vergence angle, a wide field of view, and a set of recommendation for maximum disparity and angular change for successful binocular fusion [122].

With the increased popularity of smartphones and tablet computers, multimedia content is increasingly viewed “on-the-go”. This presents several challenges for content creation. First of all, many discomfort factors are stronger on small displays [28]. Secondly, small hand-held devices can lead to fast motion, which is known to be uncomfortable [82], especially movement in depth [145]. Finally, mobile content is frequently created through automated retargetting

methods. Stereo retargeting methods have only recently started taking user comfort into account [91]. These automated methods are complicated by the fact that mobile devices are held at different distances, according to the situation and preference. Some automated systems have been proposed for hand-held telephony [100].

Since the level of discomfort depends on factors such as stereoacuity [77], algorithms for discomfort reduction are likely to become personalised, and use integrated cameras to incorporate gaze tracking for real-time processing [13].

7 Discussion

There is a large amount of data on discomfort today, and it suggests that visual discomfort and visual fatigue are very complex phenomena, encompassing many factors. Ophthalmological readings confirm a decrease in the eyes' ability to adapt as a result of fatigue. In the brain, increased activity in the parietal and occipital lobes indicates higher levels of visual processing, and fatigue has been associated with relatively low-level processing in the V3 area of the visual cortex, as well as in V4 and MT. But fatigue seems to also be related to higher cognition in the prefrontal cortex, as well as the areas related to ocular control. The resulting stress can be detected on background EEG readings, and a correlation on the autonomic nervous system has been established. All this points to large amounts of cognitive stress on many different parts of the brain.

Consequently, fatigue manifests itself through many symptoms, from dry and sore eyes to headaches, disorientation and dizziness, hinting at a wide range of causes including both ocular and neural fatigue. To our knowledge, no systematic studies linking specific symptoms to specific neurophysiological causes has been performed, but it seems apparent that the effects are interconnected and that comfortable viewing must aim to eliminate as many causes as possible.

A large body of literature has identified problematic types of content. Misalignment, excessive disparities, unnatural distortions, fast movement in depth, crosstalk and the overload of the accommodation-vergence mechanism have con-

sistently resulted in discomfort and fatigue, and much research has gone into reducing these effects. Fortunately, excessive disparities, distortions, fast movement and crosstalk can be significantly reduced or eliminated during acquisition, in postprocessing, or through better display technology. Useful sets of guidelines have been produced [103, 191], which have proved useful in reducing fatigue, but have failed to eliminate it completely [187]. Fast motion in depth and excessive disparities have been tackled by computer vision researchers, and post-processing algorithms for reducing discomfort exist [32].

Misalignment, lack of parallax cues, and the accommodation-vergence conflict are more difficult to tackle. The development of new, mobile technologies and head-mounted displays poses new challenges. Due to the mobility of hand-held devices, the viewing geometry can vary more than in a classic cinema or TV watching situation, causing misalignment. Such devices are viewed from close distances, which can lead to additional overload of the accommodation-vergence mechanism. This is especially true of head-mounted displays, which put the display very close to the eye, but simulate a natural environment and distant objects. Real-time systems which react to the viewer's position and gaze direction exist as prototypes, but represent early stages of research [35, 13]. The effect of blur on controlling accommodation could play an important role here, but only if it is fast and accurate enough to simulate natural viewing conditions without causing additional strain.

8 Conclusion

We have presented a comprehensive review of literature regarding stereoscopic viewing discomfort. We have incorporated knowledge from a variety of disciplines, as well as the latest neurophysiological findings, in order to present a complete and balanced picture of the state of research on this topic. The data suggest that there are many causes of discomfort, and that unnatural stereoscopic viewing affects all stages of visual processing. The wide range of discomfort symptoms is a natural consequence of this.

Solutions to these problems are needed if stereoscopic 3D is to become more popular.

They will require further cooperation across fields, and this cooperation has already begun, with new algorithms from image processing, new display technologies and new perceptual models for predicting and understanding discomfort. We hope that this review proves useful to researchers in this field.

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References

- [1] Advanced Television Systems Committee. Final report of the atsc planning team on 3D-TV, August 2011. PT1-049r1.
- [2] K. Akeley, S. J. Watt, A. R. Girshick, and M. S. Banks. A stereo display prototype with multiple focal distances. *ACM Trans. on Graphics*, 23:804813, 2004.
- [3] R. S. Allison. Analysis of the influence of vertical disparities arising in toed-in stereoscopic cameras. *Journal of Imaging Science & Technology*, 51:317–327, 2007.
- [4] T. L. Alvares, J. L. Semmlow, and C. Pedrono. Divergence eye movements are dependent on initial stimulus position. *Vision Research*, 45(14):1847–1855, 2005.
- [5] H. U. Amin, A. S. Malik, N. Badruddin, N. Kamel, and M. Hussain. Effects of stereoscopic 3D display technology on event-related potentials (ERPs). In *International IEEE/EMBS Conference on Neural Engineering (NER)*, pages 1084–1087, April 2015.
- [6] H. U. Amin, A. S. Malik, W. Mumtaz, N. Badruddin, and N. Kamel. Evaluation of passive polarized stereoscopic 3D display for visual and mental fatigues. In *IEEE International Conference on Engineering in Medicine and Biology Society (EMBC)*, pages 7590–7593, August 2015.
- [7] B. T. Backus, D. J. Fleet, and Parker A. J. Human cortical activity correlates with stereoscopic depth perception. *Journal of Neurophysiology*, 86(4):2054–2068, 2001.
- [8] T. Bando, A. Iijima, and S. Yano. Visual fatigue caused by stereoscopic images and the search for the requirement to prevent them: A review. *Displays*, 33(2):76 – 83, 2012.
- [9] M. S. Banks, J. Kim, and T. Shibata. Insight into vergence/accommodation mismatch. In *Proc. SPIE 8735, Head- and Helmet-Mounted Displays XVIII: Design and Applications*, volume 8735, May 2013.
- [10] M. S. Banks, J. R. Read, R. S. Allison, and S. J. Watt. Stereoscopy and the human visual system. *SMPTE Motion Imaging Journal*, 121(4):24–43, May 2012.
- [11] M. Barkowsky, J. Li, T. Han, S. Youn, J. Ok, C. Lee, C. Hedberg, I. V. Ananth, K. Wang, K. Brunnström, and P. Le Callet. Towards standardized 3DTV QoE assessment: cross-lab study on display technology and viewing environment parameters. In *Proc. SPIE 8648, Stereoscopic Displays and Applications XXIV*, volume 8648, March 2013.
- [12] Y. Bereby-Meyer, D. Leiser, and J. Meyer. Perception of artificial stereoscopic stimuli from an incorrect viewing point. *Perception and Psychophysics*, 61:1555–1563, 1999.
- [13] M. Bernhard, C. Dell'mour, M. Hecher, E. Stavrakis, and M. Wimmer. The effects of fast disparity adjustment in gaze-controlled stereoscopic applications. In *Proceedings of the Symposium on Eye Tracking Research and Applications, ETRA '14*, pages 111–118, New York, 2014. ACM.
- [14] F. Biocca, P. David, and M. West. *Continuous response measurement (CRM): a computerized tool for research on the cognitive processing of communication messages*, pages 15–64. Lawrence Erlbaum Associates, Inc., NJ, 1994.
- [15] C. Blakemore. The range and scope of binocular depth discrimination in man.

- Journal of Physiology*, 211(3):599–622, 1970.
- [16] W. Blohm, I. P. Beldie, K. Schenke, K. Fazel, and S. Pastoor. Stereoscopic image representation with synthetic depth of field. *Journal of the Society for Information Display*, 5(3):307–313, 1997.
- [17] A. S. Boydston, J. A. Rogers, L. M. Tripp, and R. Patterson. Stereoscopic depth perception survives significant interocular luminance differences. *Journal of the Society for Information Display*, 17(5):467–471, 2009.
- [18] F. Bracco, C. Chiorri, D. Glowinski, B. Hosseini Nia, and G. Vercelli. Investigating visual discomfort with 3D displays: The stereoscopic discomfort scale. In *CHI ’13 Extended Abstracts on Human Factors in Computing Systems*, CHI EA ’13, pages 307–312, New York, 2013. ACM.
- [19] M. F. Bradshaw and B. J. Rogers. Sensitivity to horizontal and vertical corrugations defined by binocular disparity. *Vision Res.*, 39(18):3049–3056, 1999.
- [20] A. Brookes and K. Stevens. The analogy between stereo depth and brightness. *Perception*, 18(5):601–614, 1989.
- [21] I. Bülthoff, H. Bülthoff, and P. Sinha. Top-down influences on stereoscopic depth-perception. *Nature Neuroscience*, 1:254–257, 1998.
- [22] C. Chen, J. Wang, K. Li, Y. Liu, and X. Chen. Visual fatigue caused by watching 3DTV: an fMRI study. *BioMedical Engineering OnLine*, 14, 2015.
- [23] C. Chen, J. Wang, K. Li, Q. Wu, H. Wang, Z. Qian, and N. Gu. Assessment visual fatigue of watching 3DTV using EEG power spectral parameters. *Displays*, 35(5):266–272, December 2014.
- [24] C. X. Chen, K. Li, Q. Wu, H. Wang, Z. Qian, and G. Sudlow. EEG-based detection and evaluation of fatigue caused by watching 3DTV. *Displays*, 34(2):81–88, 2013.
- [25] F. H. Chen, K. C. Huang, L. C. Lin, Y. H. Chou, and K. Lee. System crosstalk measurement of a time-sequential 3D display using ideal shutter glasses. In *Proc. SPIE 7863, Stereoscopic Displays and Applications XXII*, volume 7863, February 2011.
- [26] M. J. Chen, D. K. Kwon, and A. C. Bovik. Study of subject agreement on stereoscopic video quality. In *Image Analysis and Interpretation (SSIAI), 2012 IEEE Southwest Symposium on*, pages 173–176, April 2012.
- [27] A. Cho, T. Iwasaki, and K. Noro. A study on visual characteristics of binocular 3-D images. *Ergonomics*, 39(11):1285–1293, 1996.
- [28] S. H. Cho and H. B. Kang. The measurement of eyestrain caused from diverse binocular disparities, viewing time and display sizes in watching stereoscopic 3D content. In *IEEE International Conference on Computer Vision and Pattern Recognition Workshops (CVPRW)*, pages 23–28, June 2012.
- [29] S. H. Cho and H. B. Kang. Subjective evaluation of visual discomfort caused from stereoscopic 3D video using perceptual importance map. In *TENCON 2012 - 2012 IEEE Region 10 Conference*, pages 1–6, November 2012.
- [30] S. H. Cho and H. B. Kang. An analysis of visual discomfort caused by watching stereoscopic 3D content in terms of depth, viewing time and display size. *Journal of Imaging Science and Technology*, 59(2):20503–1–20503–16, March 2015.
- [31] B. G. Cumming and S. J. Judge. Disparity-induced and blur-induced convergence eye movement and accommodation in the monkey. *Journal of Neurophysiology*, 55:896–914, 1986.
- [32] P. Didyk, T. Ritschel, E. Eisemann, K. Myszkowski, and H. P. Seidel. A perceptual model for disparity. *ACM Trans. on Graphics (Proceedings SIGGRAPH 2011, Vancouver)*, 30(4), 2011.

- [33] P. Didyk, T. Ritschel, E. Eisemann, K. Myszkowski, H. P. Seidel, and W. Matusik. A luminance-contrast-aware disparity model and applications. *ACM Trans. Graph.*, 31(6):184:1–184:10, November 2012.
- [34] S. P. Du, B. Masia, S. M. Hu, and D. Gutierrez. A metric of visual comfort for stereoscopic motion. *ACM Trans. Graph.*, 32(6):222:1–222:9, November 2013.
- [35] A. T. Duchowski, D. H. House, J. Gestring, R. I. Wang, K. Krejtz, I. Krejtz, R. Mantiuk, and B. Bazyluk. Reducing visual discomfort of 3D stereoscopic displays with gaze-contingent depth-of-field. In *Proceedings of the ACM Symposium on Applied Perception*, SAP ’14, pages 39–46, New York, NY, USA, 2014. ACM.
- [36] M. Emoto, T. Niida, and F. Okano. Repeated vergence adaptation causes the decline of visual functions in watching stereoscopic television. *Journal of Display Technology*, 1:328340, 2005.
- [37] E. F. Fincham and J. Walton. The reciprocal actions of accommodation and convergence. *The Journal of Physiology*, 137:488–508, 1957.
- [38] R. A. Fisher. Theory of statistical estimation. *Mathematical Proceedings of the Cambridge Philosophical Society*, 22:700–725, 1925.
- [39] J. Frey, L. Pommereau, F. Lotte, and M. Hachet. Assessing the zone of comfort in stereoscopic displays using EEG. In *CHI ’14 Extended Abstracts on Human Factors in Computing Systems*, CHI EA ’14, pages 2041–2046, New York, 2014. ACM.
- [40] G. Fry. Further experiments on the accommodative convergence relationship. *American Journal of Optometry*, 16:325–334, 1939.
- [41] A. Glennerster, L. Tcheang, S. J. Gilson, A. W. Fitzgibbon, and A. J. Parker. Humans ignore motion and stereo cues in favor of a fictional stable world. *Current Biology*, 16:428–432, 2006.
- [42] E. Haapalainen, S. Kim, J. F. Forlizzi, and A. K. Dey. Psycho-physiological measures for assessing cognitive load. In *LNCS*, pages 301–310. Springer, September 2010.
- [43] W. Hachicha, A. Beghdadi, and F. A. Cheikh. Stereo image quality assessment using a binocular just noticeable difference model. In *IEEE International Conference on Image Processing (ICIP)*, pages 113–117, September 2013.
- [44] H. Hagura, M. Nakajima, T. Owaki, and T. Takeda. Study of asthenopia caused by the viewing of stereoscopic images: measurement by MEG and other devices. *Proc. SPIE*, 6057:192–202, 2006.
- [45] R. Hamberg and H. de Ridder. Continuous assessment of perceptual image quality. *Journal of the Optical Society of America*, 12:2573–2577, 1995.
- [46] B. Hartle, A. Lugtigheid, A. Kazimi, R. S. Allison, and L. M. Wilcox. Preference for motion and depth in 3D film. In *Proc. SPIE 9391, Stereoscopic Displays and Applications XXVI*, volume 9391, March 2015.
- [47] H. Heuer. Apparent motion in depth resulting from changing size and changing vergence. *Perception*, 16(3):337350, 1987.
- [48] N. Hiruma and T. Fukuda. Accommodation response to binocular stereoscopic TV images and their viewing conditions. *SMPTE Journal*, pages 1137–1144, December 1993.
- [49] D. M. Hoffman, A. R. Girshick, K. Akelley, and M. S. Banks. Vergence-accommodation conflicts hinder visual performance and cause visual fatigue. *Journal of Vision*, 8(3:33):130, 2008.
- [50] N. Holliman, C. Baugh, C. Frenk, A. Jenkins, B. Froner, D. Hassaine, J. Helly, N. Metcalfe, and T. Okamoto. Cosmic cookery: making a stereoscopic 3D animated movie. In *Stereoscopic Displays and Virtual Reality Systems XIII. Proceedings*

- of the SPIE*, volume 6055, pages 34–45, February 2006.
- [51] I. P. Howard, X. Fang, R. S. Allison, and J. E. Zacher. Effects of stimulus size and eccentricity on horizontal and vertical vergence. *Exp. Brain Res.*, 130:124–132, 2000.
- [52] I. P. Howard and B. J. Rogers. *Depth perception*. Porteous, Toronto, 2002.
- [53] P. A. Howarth. Potential hazards of viewing 3-d stereoscopic television, cinema and computer games: a review. *Ophthalmic & Physiological Optics*, 31:111–122, 2011.
- [54] K. Huang, K. Lee, and H. Lin. Crosstalk issue in stereo/autostereoscopic display. In *International Display Manufacturing Conference*, pages 2–18, 2009.
- [55] A. D. Hwang and E. Peli. Instability of the perceived world while watching 3D stereoscopic imagery: A likely source of motion sickness symptoms. *i-Perception*, 5(6):515–535, October 2014.
- [56] I. Iatsun, M. C. Larabi, and C. Fernandez-Maloigne. Investigation of visual fatigue/discomfort generated by S3D video using eye-tracking data. In *Proc. SPIE 8648, Stereoscopic Displays and Applications XXIV*, volume 8648, March 2013.
- [57] I. Iatsun, M. C. Larabi, and C. Fernandez-Maloigne. Investigation and modeling of visual fatigue caused by S3D content using eye-tracking. *Displays*, 39:11–25, October 2015.
- [58] W. IJsselsteijn, H. de Ridder, R. Hamberg, D. Bouwhuis, and J. Freeman. Perceived depth and the feeling of presence in 3DTV. *Displays*, 18:207–214, 1998.
- [59] W. A. IJsselsteijn, P. H. J. Seuntiens, and L. M. J. Meesters. *Human Factors of 3D Displays*, pages 219–234. John Wiley and Sons, New York, 2005.
- [60] ITU. Methodology for the subjective assessment of the quality of television pictures, ITU recommendation BT.500-11, 2002.
- [61] T. Iwasaki and A. Tawara. Effects of viewing distance on accommodative and pupillary responses following a three-dimensional task. *Ophthalmic and Physiological Optics*, 22(2):113–118, 2002.
- [62] Q. Jiang, F. Shao, G. Jiang, M. Yu, Z. Peng, and C. Yu. A depth perception and visual comfort guided computational model for stereoscopic 3D visual saliency. *Signal Processing: Image Communication*, 38:57–69, October 2015.
- [63] G. R. Jones, D. Lee, N. S. Holliman, and D. Ezra. Controlling perceived depth in stereoscopic images. In *Stereoscopic Displays and Virtual Reality Systems VIII, Proceedings of the SPIE*, volume 4297, pages 42–53, June 2001.
- [64] Y. Jung, H. Sohn, S. I. Lee, and Y. Ro. Visual comfort improvement in stereoscopic 3D displays using perceptually plausible assessment metric of visual comfort. *IEEE Trans. on Consumer Electronics*, 60(1):1–9, February 2014.
- [65] Y. J. Jung, D. Kim, H. Sohn, S. I. Lee, and H. W. Park. Subjective and objective measurements of visual fatigue induced by excessive disparities in stereoscopic images. *Proc. SPIE Stereoscopic Displays and Applications XXIV*, 8648, March 2013.
- [66] Y. J. Jung, D. Kim, H. Sohn, S. I. Lee, H. W. Park, and Y. M. Ro. Towards a physiology-based measure of visual discomfort: Brain activity measurement while viewing stereoscopic images with different screen disparities. *Journal of Display Technology*, 11(9):730–743, September 2015.
- [67] Y. J. Jung, H. Sohn, S. I. Lee, H. W. Park, and Y. M. Ro. Predicting visual discomfort of stereoscopic images using human attention model. *IEEE Trans. on Circuits and Systems for Video Technology*, 23(12):2077–2082, Dec 2013.
- [68] D. Kane, R. T. Held, and M. S. Banks. Visual discomfort with stereo 3D displays when the head is not upright. *Proc. SPIE*, 8288:828814–828814–10, 2012.

- [69] C. J. Kim, S. Park, M. J. Won, M. Whang, and E. C. Lee. Autonomic nervous system responses can reveal visual fatigue induced by 3d displays. *Sensors*, 13(10):13054–13062, October 2013.
- [70] D. Kim, S. Choi, S. Park, and K. Sohn. Stereoscopic visual fatigue measurement based on fusional response curve and eye-blanks. In *International Conference on Digital Signal Processing (DSP)*, pages 1–6, July 2011.
- [71] D. Kim, S. Choi, and K. Sohn. Effect of vergence accommodation conflict and parallax difference on binocular fusion for random dot stereogram. *IEEE Trans. on Circuits and Systems for Video Technology*, 22(5):811–816, May 2012.
- [72] D. Kim, Y. J. Jung, Y. Han, J. Choi, E. Kim, B. S. Jeong, Y. M. Ro, and H. W. Park. fMRI analysis of excessive binocular disparity on the human brain. *International Journal of Imaging Systems and Technology*, 24(1):94–102, March 2014.
- [73] D. Kim, Y. J. Jung, E. Kim, Y. M. Ro, and H. W. Park. Human brain response to visual fatigue caused by stereoscopic depth perception. In *International Conference on Digital Signal Processing (DSP)*, pages 1–5, July 2011.
- [74] D. W. Kim, J. S. Yoo, and Y. H. Seo. Qualitative analysis of individual and composite content factors of stereoscopic 3D video causing visual discomfort. *Displays*, 34(3):223–240, July 2013.
- [75] H. Kim and S. Lee. Transition of visual attention assessment in stereoscopic images with evaluation of subjective visual quality and discomfort. *IEEE Trans. on Multimedia*, 17(12):2198–2209, December 2015.
- [76] J. Kim, D. Kane, and M. S. Banks. The rate of change of vergenceaccommodation conflict affects visual discomfort. *Vision Research*, 105:159–165, December 2014.
- [77] S. H. Kim, Y. W. Suh, C. Yun, E. J. Yoo, J. H. Yeom, and Y. A. Cho. Influence of stereopsis and abnormal binocular vision on ocular and systemic discomfort while watching 3D television. *Eye*, 27:1243–1248, 2013.
- [78] Y. J. Kim and E. C. Lee. EEG based comparative measurement of visual fatigue caused by 2D and 3D displays. *Commun. Comput. Info. Sci.*, 174:289–292, 2011.
- [79] F. L. Kooi and A. Toet. Visual comfort of binocular and 3-D displays. *Displays*, 25:99108, 2004.
- [80] M. Lambooij, M. F. Fortuin, W. A. IJsselsteijn, and I. Heynderickx. Reading performance as screening tool for visual complaints from stereoscopic content. *Displays*, 33(2):84–90, April 2012.
- [81] M. Lambooij, W. Ijsselsteijn, M. Fortuin, and I. Heynderickx. Visual discomfort and visual fatigue of stereoscopic displays: A review. *Journal of Imaging Science and Technology*, 53(3):114, 2009.
- [82] M. Lambooij, W. A. IJsselsteijn, and I. Heynderickx. Visual discomfort of 3D TV: Assessment methods and modeling. *Displays*, 32(4):209 – 218, 2011. Visual Image Safety.
- [83] M. Lambooij, M. J. Murdoch, W. A. IJsselsteijn, and I. Heynderickx. The impact of video characteristics and subtitles on visual comfort of 3D TV. *Displays*, 34(1):816, January 2013.
- [84] M. Lang, A. Hornung, O. Wang, S. Poulakos, A. Smolic, and M. Gross. Nonlinear disparity mapping for stereoscopic 3D. *ACM Trans. on Graphics*, 29(3):10, 2010.
- [85] E. C. Lee, H. Heo, and K. R. Park. The comparative measurements of eyestrain caused by 2D and 3D displays. *IEEE Trans. Consumer Electronics*, 56(3):1677–1683, August 2010.
- [86] J. H. Lee and J. K. Song. Individual variation in 3d visual fatigue caused by stereoscopic images. *IEEE Trans. Consumer Electronics*, 58(2):500–504, May 2012.

- [87] S. I. Lee, Y. J. Jung, H. Sohn, and Y. M. Ro. Experimental investigation of discomfort combination: toward visual discomfort prediction for stereoscopic videos. *Journal of Electronic Imaging*, 23(1), January 2014.
- [88] S. I. Lee, Y. J. Jung, H. Sohn, Y. M. Ro, and H. W. Park. Visual discomfort induced by fast salient object motion in stereoscopic video. In *Proc. SPIE 7863, Stereoscopic Displays and Applications XXII*, volume 7863, February 2011.
- [89] S. I. Lee, Y. J. Jung, H. Sohn, F. Speranza, and Y. M. Ro. Effect of stimulus width on the perceived visual discomfort in viewing stereoscopic 3-D-TV. *IEEE Trans. on Broadcasting*, 59(4):580–590, December 2013.
- [90] L. Leroy, P. Fuchs, and G. Moreau. Visual fatigue reduction for immersive stereoscopic displays by disparity, content, and focus-point adapted blur. *IEEE Trans. on Industrial Electronics*, 59(10):3998–4004, October 2012.
- [91] D. Li, X. Qiao, D. Zang, L. Wang, and M. Zhang. On adjustment of stereo parameters in multiview synthesis for planar 3D displays. *Journal of the Society for Information Display*, 2015.
- [92] H. C. O. Li, J. Seo, K. Kham, and S. Lee. Measurement of 3D visual fatigue using event-related potential (ERP): 3D oddball paradigm. In *Proc. 3DTV Conf.: The True VisionCapture, Transmission and Display of 3D Video*, pages 193–196, May 2008.
- [93] J. Li, M. Barkowsky, and P. Le Callet. The influence of relative disparity and planar motion velocity on visual discomfort of stereoscopic videos. In *International Workshop on Quality of Multimedia Experience (QoMEX)*, pages 155–160, September 2011.
- [94] J. Li, M. Barkowsky, and P. Le Callet. Visual discomfort is not always proportional to eye blinking rate: exploring some effects of planar and in-depth motion on 3DTV QoE. In *International Workshop on Video Processing and Quality Metrics for Consumer Electronics VPQM 2013*, pages 1–6, Scottsdale, January 2013.
- [95] J. Li, M. Barkowsky, and P. Le Callet. Visual discomfort of stereoscopic 3D videos: Influence of 3D motion. *Displays*, 35(1):49–57, January 2014.
- [96] J. Li, M. Barkowsky, and P. Le Callet. Visual discomfort in 3DTV: Definitions, causes, measurement, and modeling. In A. Kondoz and T. Dagiuklas, editors, *Novel 3D Media Technologies*, pages 185–209. Springer New York, 2015.
- [97] H. C. Longuet-Higgins. A computer algorithm for reconstructing a scene from two projections. *Nature*, 293:133–135, 1981.
- [98] J. López, J. Rodrigo, D. Jiménez, and J. Méndez. Stereoscopic 3D video quality assessment based on depth maps and video motion. *EURASIP Journal on Image and Video Processing*, 2013(1), 2013.
- [99] C. Y. Ma and H. M. Hang. Learning-based saliency model with depth information. *Journal of Vision*, 15(6), May 2015.
- [100] S. Mangiat and J. Gibson. Disparity remapping for handheld 3D video communications. In *IEEE International Conference on Emerging Signal Processing Applications (ESPA)*, pages 147–150, January 2012.
- [101] T. G. Martens and K. N. Ogle. Observations on accommodative convergence: Especially its nonlinear relationships. *American Journal of Ophthalmology*, 47:455–463, 1959.
- [102] D. F. McAllister. *Stereo computer graphics: and other true 3D technologies*. Princeton University Press, Princeton, NJ, 1993.
- [103] B. Mendiburu. *3D Movie Making: Stereoscopic digital cinema from script to screen*. Focal Press, 2009.

- [104] A. K. Moorthy and A. C. Bovik. A survey on 3D quality of experience and 3D quality assessment. In *Proc. SPIE 8651, Human Vision and Electronic Imaging XVIII*, volume 8651, March 2013.
- [105] J. Moss and E. Muth. Characteristics of head mounted displays and their effects on simulator sickness. *Human Factors*, 53(3):308–319, 2011.
- [106] S. Mun, M. Park, S. Park, and M. Whang. SSVEP and ERP measurement of cognitive fatigue caused by stereoscopic 3D. *Neuroscience Letters*, 525(2):89–94, September 2012.
- [107] H. Murray. 3D animation in three dimensions: the rocky road to the obvious. In *Stereoscopic Displays and Applications XIII. Proceeding of the SPIE*, volume 6803, February 2006.
- [108] Yang S. N., Schlieski T., Selmins B., Cooper S., Doherty R., Corriveau P. J., and Sheedy J. E. Individual differences and seating position affect immersion and symptom in stereoscopic 3D viewing. In *Proceeding of Stereoscopic Display and Application*, volume 7863, pages 1–44, 2011.
- [109] S. A. A. Naqvi, N. Badruddin, A. S. Malik, W. Hazabbah, and B. Abdullah. Does 3D produce more symptoms of visually induced motion sickness? In *International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*, pages 6405–6408, July 2013.
- [110] P. Neri, H. Bridge, and D. J. Heeger. Stereoscopic processing of absolute and relative disparity in human visual cortex. *Journal of Neurophysiology*, 92:1880–1891, April 2004.
- [111] P. Neveu, M. Philippe, A. E. Priot, P. Fuchs, and C. Roumes. Vergence tracking: a tool to assess oculomotor performance in stereoscopic displays. *Journal of Eye Movement Research*, 5(2):1–8, 2012.
- [112] Y. Nojiri, H. Yamanoue, A. Hanazato, M. Emoto, and F. Okano. Visual comfort/discomfort and visual fatigue caused by stereoscopic HDTV viewing. *Proc. SPIE*, 5291:303–313, January 2004.
- [113] Y. Nojiri, H. Yamanoue, A. Hanazato, and F. Okano. Measurement of parallax distribution, and its application to the analysis of visual comfort for stereoscopic HDTV. *Proc. SPIE*, 5006:195–205, 2003.
- [114] Y. Nojiri, H. Yamanoue, S. Ide, S. Yano, and F. Okano. Parallax distribution and visual comfort on stereoscopic HDTV. In *Proc. IBC*, pages 373–380, 2006.
- [115] K. N. Ogle. Induced size effect I: A new phenomenon in binocular vision associated with the relative size of the images in the two eyes. *Archives of Ophthalmology*, 20:604, 1938.
- [116] C. Oh, B. Ham, S. Choi, and K. Sohn. Visual fatigue relaxation for stereoscopic video via nonlinear disparity remapping. *IEEE Trans. on Broadcasting*, 61(2):142–153, June 2015.
- [117] L. O’Hare, T. Zhang, H. T. Nefs, and P. B. Hibbard. Visual discomfort and depth-of-field. *i-Perception*, 4(3):156–169, 2013.
- [118] Y. Okada, K. Ukai, J. S. Wolffsohn, B. Gilmartin, A. Iijima, and T. Bando. Target spatial frequency determines the response to conflicting defocus- and convergence-driven accommodative stimuli. *Vision Research*, 46:475–484, 2006.
- [119] S.E. Palmer. *Vision Science: Photons to Phenomenology*. The MIT Press, 1999.
- [120] M. C. Park and S. Mun. Overview of measurement methods for factors affecting the human visual system in 3D displays. *Journal of Display Technology*, 11(11):877–888, November 2015.
- [121] A. J. Parker. Binocular depth perception and the cerebral cortex. *Nature Review Neuroscience*, 8(5):379–391, May 2007.
- [122] R. Patterson, M. D. Winterbottom, and B. J. Pierce. Perceptual issues in the use of head-mounted visual displays. *Human Factors*, 48(3):555–573, 2006.

- [123] E. Peli. The visual effects of head-mounted display (hmd) are not distinguishable from those of desk-top computer display. *Vision Res.*, 38:2053–2066, 1998.
- [124] E. Peli. *Optometric and perceptual issues with head-mounted display*, pages 205–276. McGraw-Hill, New York, 1999.
- [125] A. S. Percival. The relation of convergence. *Ophthalmological Review*, 11:313–328, 1892.
- [126] M. Pölönen, T. Järvenpää, and B. Bilcu. Stereoscopic 3D entertainment and its effect on viewing comfort: Comparison of children and adults. *Applied Ergonomics*, 44(1):151–160, January 2013.
- [127] M. Pölönen, M. Salmimaa, and J. Häkkinen. Effect of ambient illumination level on perceived autostereoscopic display quality and depth perception. *Displays*, 32(3):135–141, July 2011.
- [128] S. Qi and J. Ho. Shift-map based stereo image retargeting with disparity adjustment. In K. M. Lee, Y. Matsushita, J. M. Rehg, and Z. Hu, editors, *Computer Vision ACCV 2012*, volume 7727 of *Lecture Notes in Computer Science*, pages 457–469. Springer Berlin Heidelberg, 2013.
- [129] H. T. Quan, M. Barkowsky, and P. Le Callet. The importance of visual attention in improving the 3D-TV viewing experience: Overview and new perspectives. *IEEE Trans. on Broadcasting*, 57(2):421–431, Jun 2011.
- [130] C. Rashbass and G. Westheimer. Disjunctive eye movements. *Journal of Physiology*, 159(2):339–360, 1961.
- [131] J. C. A. Read and I. Bohr. User experience while viewing stereoscopic 3D television. *Ergonomics*, 57(8):1140–1153, 2014.
- [132] S. Saito, M. Sotoyama, and S. Taptagaporn. Physiological indices of visual fatigue due to vdt operation: pupillary reflexes and accommodative responses. *Industrial Health*, 32(2):57–66, 1994.
- [133] C. M. Schor. The influence of interactions between accommodation and convergence on the lag of accommodation. *Ophthalmic and Physiological Optics*, 19(2):134–150, 1999.
- [134] C. M. Schor and T. K. Tsuetaki. Fatigue of accommodation and vergence modifies their mutual interactions. *Investigative Ophthalmology and Visual Science*, 28(8):1250–1259, 1987.
- [135] C. M. Schor, I. C. Wood, and J. Ogawa. Binocular sensory fusion is limited by spatial resolution. *Vision Research*, 24:661665, 1984.
- [136] P. J.H. Seuntiens, L. M. J. Meesters, and W. A. IJsselsteijn. Perceptual attributes of crosstalk in 3D images. *Displays*, 26(4-5):177–183, October 2005.
- [137] C. Sheard. The prescription of prisms. *American Journal of Optometry*, 11:364–378, 1934.
- [138] J. E. Sheedy and J. J. Saladin. Phoria, vergence, and fixation disparity in oculomotor problems. *American Journal of Optometry and Physiological Optics*, 54:474–478, 1977.
- [139] T. Shibata, J. Kim, D. M. Hoffman, and M. S. Banks. The zone of comfort: Predicting visual discomfort with stereo displays. *Journal of Vision*, 11(8:11):129, 2011.
- [140] T. Shibata, F. Muneyuki, K. Oshima, J. Yoshitake, and T. Kawai. Comfortable stereo viewing on mobile devices. In *Proc. SPIE 8648, Stereoscopic Displays and Applications XXIV*, volume 8648, March 2013.
- [141] T. Shiomi, K. Uemoto, T. Kojima, S. Sano, H. Ishio, H. Takada, M. Omori, T. Watanabe, and M. Miyao. Simultaneous measurement of lens accommodation and convergence in natural and artificial 3D vision. *Journal of the Society for Information Display*, 21(3):120–128, March 2013.
- [142] H. Sohn, Y. J. Jung, S. I. Lee, F. Speranza, and Y. M. Ro. Disparity remapping to

- ameliorate visual comfort of stereoscopic video. In *Proc. SPIE 8648, Stereoscopic Displays and Applications XXIV*, volume 8648, March 2013.
- [143] H. Sohn, Y. J. Jung, and Y. M. Ro. Local disparity remapping to enhance depth quality of stereoscopic 3D images using stereoacuity function. In *Proc. SPIE 9011, Stereoscopic Displays and Applications XXV*, volume 9011, March 2014.
- [144] A. G. Solimini. Are there side effects to watching 3D movies? a prospective crossover observational study on visually induced motion sickness. *PLOS One*, February 2013.
- [145] F. Speranza, W. J. Tam, R. Renaud, and N. Hur. Effect of disparity and motion on visual comfort of stereoscopic images. *Proceedings of the SPIE*, 6055, 2006.
- [146] L. B. Stelmach, W. J. Tam, D. V. Meegan, and A. Vincent. Stereo image quality: effects of mixed spatio-temporal resolution. *IEEE Trans. on Circuits and Systems for Video Technology*, 10(2):188–193, 2000.
- [147] C. C. Su, A. K. Moorthy, and A. C. Bovik. Visual quality assessment of stereoscopic image and video: Challenges, advances, and future trends. In C. Deng, L. Ma, W. Lin, and K. N. Ngan, editors, *Visual Signal Quality Assessment*, pages 185–212. Springer International Publishing, 2015.
- [148] Y. Suzuki, Y. Onda, S. Katada, S. Ino, and T. Ifukube. Effects of an eyeglass-free 3-D display on the human visual system. *Japanese Journal of Ophthalmology*, 48(1):1–6, 2004.
- [149] W. J. Tam, F. Speranza, C. Vázquez, R. Renaud, and N. Hur. Visual comfort: stereoscopic objects moving in the horizontal and mid-sagittal planes. In *Proc. SPIE 8288, Stereoscopic Displays and Applications XXIII*, volume 8288, February 2012.
- [150] K. Terzić, D. Lobato, M. Saleiro, J. Martins, M. Farrajota, J.M.F. Rodrigues, and J.M.H. du Buf. Biological models for active vision: Towards a unified architecture. In *ICVS 2013, LNCS*, volume 7963, pages 113–122, July 2013.
- [151] K. Terzić, J.M.F. Rodrigues, and J.M.H. du Buf. BIMP: A real-time biological model of multi-scale keypoint detection in V1. *Neurocomputing*, 150:227–237, 2015.
- [152] M. Torii, Y. Okada, K. Ukai, J. S. Wolffsohn, and B. Gilmartin. Dynamic measurement of accommodative responses while viewing stereoscopic images. *Journal of Modern Optics*, 55(4-5):557–567, 2008.
- [153] I. Tsirlin, R. S. Allison, and L. M. Wilcox. Crosstalk reduces the amount of depth seen in 3D images of natural scenes. In *Proc. SPIE 8288, Stereoscopic Displays and Applications XXIII*, volume 8288, February 2012.
- [154] I. Tsirlin, L. M. Wilcox, and R. S. Allison. The effect of crosstalk on the perceived depth from disparity and monocular occlusions. *IEEE Trans. on Broadcasting*, 57(2):445–453, June 2011.
- [155] C. W. Tyler, L. T. Likova, K. Atanassov, V. Ramachandra, and S. Goma. 3D discomfort from vertical and torsional disparities in natural images. In *Proc. SPIE 8291, Human Vision and Electronic Imaging XVII*, volume 8291, February 2012.
- [156] K. Ukai and P. A. Howarth. Visual fatigue caused by viewing stereoscopic motion images: Background, theories and observations. *Displays*, 29:106116, 2008.
- [157] K. Ukai and Y. Kato. The use of video refraction to measure the dynamic properties of the near triad in observers of a 3-D display. *Ophthalmic and Physiological Optics*, 22(5):385–388, 2002.
- [158] K. Ukai and A. Kibe. Counterroll torsional eye movement in users of head-mounted displays. *Displays*, 24:59–63, 2003.
- [159] M. Urvoy, M. Barkowsky, and P. Le Callet. How visual fatigue and discomfort impact 3D-TV quality of experience: a comprehensive review of technological, psychophysical, and psychological factors. *An-*

- nals of Telecommunications*, 68:641–655, 2013.
- [160] C. Vienne, L. Blondé, and D. Doyen. Visual fatigue versus eye-movements. In *Proc. SPIE, Stereoscopic Displays and Applications XXIII*, volume 8288, February 2012.
- [161] A. Voronov, D. Vatolin, D. Sumin, V. Nappadovsky, and A. Borisov. Methodology for stereoscopic motion-picture quality assessment. In *Proc. SPIE 8648, Stereoscopic Displays and Applications XXIV*, volume 8648, March 2013.
- [162] F. J. Wang, X. Z. Sang, Y. D. Liu, G. Z. Shi, and D. X. Xu. Visual fatigue evaluation based on depth in 3D videos. In *Proc. SPIE 8913, Optical Storage and Display Technology*, volume 8913, August 2013.
- [163] J. Wang, M. P. DaSilva, P. Le Callet, and V. Ricordel. Computational model of stereoscopic 3D visual saliency. *IEEE Trans. on Image Processing*, 22(6):2151–2165, June 2013.
- [164] L. Wang, K. Teunissen, Y. Tu, L. Chen, P. Zhang, T. Zhang, and I. Heynderickx. Crosstalk evaluation in stereoscopic displays. *Journal of Display Technology*, 7(4):208–214, April 2011.
- [165] L. Wang, Y. Tu, L. Chen, P. Zhang, K. Teunissen, and I. Heynderickx. Cross-talk acceptability in natural still images for different (auto) stereoscopic display technologies. *Journal of the SID*, 18(6):405–414, 2010.
- [166] L. Wang, Y. Tu, L. Chen, P. Zhang, T. Zhang, K. Teunissen, and I. Heynderickx. Effect of display technology on the crosstalk perception in stereoscopic video content. *IEEE Trans. on Circuits and Systems for Video Technology*, 22(9):1257–1265, September 2012.
- [167] Q. Wang, Q. H. Wang, and Y. C. Liao. Relationship between age differences and display parameters on visual comfort for autostereoscopic display. *Journal of the Society for Information Display*, 23(2):69–75, February 2015.
- [168] C. Ware, C. Gobrecht, and M. A. Paton. Dynamic adjustment of stereo display parameters. *IEEE Trans. on Systems, Man and Cybernetics*, 28:56–65, January 1998.
- [169] S. J. Watt, K. Akeley, M. O. Ernst, and M. S. Banks. Focus cues affect perceived depth. *Journal of Vision*, 5:834–862, 2005.
- [170] S. W. Wee, N. J. Moon, W. K. Lee, and S. Jeon. Ophthalmological factors influencing visual asthenopia as a result of viewing 3D displays. *British Journal of Ophthalmology*, 96(11):1391–1394, 2012.
- [171] A. E. Welchman, A. Deubelius, V. Conrad, H. H. Bültlhoff, and Z. Kourtzi. 3d shape perception from combined depth cues in human visual cortex. *Nature Neuroscience*, 8:820–827, May 2005.
- [172] S. P. Williams and R. V. Parrish. New computational control techniques and increased understanding for stereo 3D displays. In *Proceedings of SPIE Stereoscopic Displays and Applications*, pages 73–82, 1990.
- [173] S. Winkler and D. Min. Stereo/multiview picture quality: Overview and recent advances. *Signal Processing: Image Communication*, 28(10):1358–1373, November 2013.
- [174] A. Woods, T. Docherty, and R. Koch. Image distortions in stereoscopic video systems. In *Proceedings of the SPIE*, volume 1915, pages 36–49, 1993.
- [175] M. Wopking. Viewing comfort with stereoscopic pictures: An experimental study on the subjective effects of disparity magnitude and depth of focus. *Journal of the SID*, 3(3):101–103, 1995.
- [176] L. Xing, J. You, T. Ebrahimi, and A. Perkis. Assessment of stereoscopic crosstalk perception. *IEEE Trans. on Multimedia*, 14(2):326–337, April 2012.

- [177] T. Yamazaki, K. Kamijo, and S. Fukuzumi. Quantitative evaluation of visual fatigue encountered in viewing stereoscopic 3D displays: near-point distance and visual evoked potential study. *Proc. SID*, 31(3):245–247, 1990.
- [178] T. Yan, R. W. H. Lau, Y. Xu, and L. Huang. Depth mapping for stereoscopic videos. *International Journal of Computer Vision*, 102(1-3):293–307, 2013.
- [179] S. Yang, T. Schlieski, S. Cooper, R. Doherty, P. J. Corriveau, and J. E. Sheedy. Individual differences and seating position affect immersion and symptoms in stereoscopic 3d viewing. *Optometry and Vision Science*, 89(7), 2012.
- [180] S. N. Yang, T. Schlieski, B. Selmins, S. C. Cooper, R. A. Doherty, P. J. Corriveau, and J. E. Sheedy. Stereoscopic viewing and reported perceived immersion and symptoms. *Optometry Vis. Sci.*, 89(7):1068–1080, July 2012.
- [181] S. Yano, M. Emoto, and T. Mitsuhashi. Two factors in visual fatigue caused by stereoscopic HDTV images. *Displays*, 25:141–150, 2004.
- [182] S. Yano, S. Ide, T. Mitsuhashi, and H. Thwaites. A study of visual fatigue and visual comfort for 3D HDTV/HDTV images. *Displays*, 23:191–201, 2002.
- [183] Y. Y. Yeh and L. D. Silverstein. Limits of fusion and depth judgment in stereoscopic color displays. *Human Factors*, 32(1):45–60, 1990.
- [184] J. H. Yu, B. H. Lee, and D. H. Kim. EOG-based eye movement measure of visual fatigue caused by 2D and 3D displays. In *Biomedical and Health Informatics (BHI), 2012 IEEE-EMBS International Conference on*, pages 305–308, January 2012.
- [185] J. D. Yun, Y. Kwak, and S. Yang. Evaluation of perceptual resolution and crosstalk in stereoscopic displays. *Journal of Display Technology*, 9(2):106–111, Feb 2013.
- [186] F. Zafar and A. Badano. Characterization of crosstalk in stereoscopic display devices. *Journal of the Society for Information Display*, 22(12):613–622, 2014.
- [187] F. Zeri and S. Livi. Visual discomfort while watching stereoscopic three-dimensional movies at the cinema. *Ophthalmic and Physiological Optics*, 35(3):271–282, May 2015.
- [188] X. Zhang, J. Zhou, J. Chen, X. Guo, Y. Zhang, and X. Gu. Visual comfort assessment of stereoscopic images with multiple salient objects. In *IEEE International Symposium on Broadband Multimedia Systems and Broadcasting (BMSB)*, pages 1–6, June 2015.
- [189] C. Zhao, C. Zheng, M. Zhao, Y. Tu, and J. Liu. Multivariate autoregressive models and kernel learning algorithms for classifying driving mental fatigue based on electroencephalographic. *Expert System Applications*, 38(3):1859–1865, 2011.
- [190] J. Zhou, Y. Bi, J. Chen, Q. Chen, and Y. Qin. Comfort assessment of border effects in stereoscopic images. In *IEEE International Symposium on Broadband Multimedia Systems and Broadcasting (BMSB)*, pages 1–6, June 2014.
- [191] F. Zilly, J. Kluger, and P. Kauff. Production rules for stereo acquisition. *Proceedings of the IEEE*, 99(4):590–606, April 2011.
- [192] B. Zou, Y. Liu, M. Guo, and Y. Wang. EEG-based assessment of stereoscopic 3D visual fatigue caused by vergence-accommodation conflict. *Journal of Display Technology*, 11(12):1076–1083, December 2015.