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Visual discomfort of 3D TV: Assessment methods and modeling

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ABSTRACT

To gain knowledge on how visual discomfort is built up while watching stereoscopic content an experiment was designed with two objectives: (1) to compare the continuous evaluation method with other assessment methods that potentially can substitute the continuous evaluation for the assessment of visual discomfort of e.g., feature-length movies, and (2) to relate the impact of time-variant content characteristics, such as motion and disparity, to the assessment of visual discomfort.

In an experiment a 24 min 3D movie 'Spy Kids 3-D: game over' converted from 2D to 3D was displayed on a 9-view autostereoscopic lenticular LCD, and continuously assessed in terms of visual comfort by 24 participants. Additional assessment methods included the assessment of six 10 s sequences captured from the 3D movie and a single retrospective assessment of the entire 3D movie. Time-variant content characteristics, such as derivatives of motion and screen disparity values, were extracted from the 3D movie with motion and depth estimation algorithms. The moment-to-moment values of these characteristics were correlated to the continuous assessment scores of visual discomfort.

With respect to the first objective, results reveal that the correlation between the assessment of the 10 s sequences captured from the 3D movie and their corresponding part within the continuous assessment is low, whereas the correlation between the retrospective assessment and the mean of the continuous assessment score over scene parts with a high screen disparity is higher. With respect to the second objective, for static scenes the visual comfort can be largely described by the screen disparity offset and range. For dynamic scenes the visual comfort is largely related to the screen disparity range, lateral motion and to the change in screen disparity.

1. Introduction

Though optimizing aspects of image quality, e.g., resolution, dynamic range and color gamut, remains one of the main goals in the development of imaging systems nowadays, improving the overall viewing experience gains attention in research on innovative, next-generation displays such as AmbiLight and three-dimensional television (3D TV) [1]. In the case of 3D TV, the improvement in viewing experience is based on the principle of binocular disparity; the human eyes are horizontally separated, and therefore, have their own perspective of the world. They receive slightly different retinal images, from which the brain extracts relative stereoscopic depth information. 3D TV exploits this concept by providing different views for each eye, resulting in content that is rendered in depth and projected both in front of and behind the display. There are different technologies to realize this, such as color or polarization filters to separate the left and right eye views. More innovative display technologies that do not require viewers to wear glasses, allow motion parallax and allow multiple viewers simultaneously, are so-called autostereoscopic displays, in which flat displays [2], e.g., based on lenticulars or head-tracking, and volumetric displays [3] can be distinguished. Such innovative display technologies require evaluation of their benefits and drawbacks from a consumer point of view. Several authors have acknowledged that it is essential that stereoscopic content must be evaluated in terms of evaluation metrics that reflect the full extent of the viewer's experience [4–13]. Hence, visual discomfort, one of the unwanted side-effects of rendering stereoscopic content, and its relation with individuals' self-appraisal must be evaluated on a perceptual basis.

Visual discomfort can be induced by excessive screen disparity (i.e., the angular distance between two corresponding pixels in two separate views on a stereoscopic display). Even within a screen disparity range of comfortable viewing (i.e., within 1° of disparity), however, visual discomfort may still occur [13]. Few of the most pertinent determinants are 3D artifacts, unnatural blur and an excessive demand on the accommodation–convergence (AC) linkage caused by fast motion in depth [12,13]. These determinants are all related to some extent to certain video content characteristics

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[13–15], and as a consequence, their impact fluctuates in time. It is also assumed that the degree of visual discomfort increases during prolonged viewing [13,16], which to our knowledge has never been confirmed. There are studies that explore long-term effects of visual fatigue in general, e.g., experienced when viewing chromatic displays [17] or whilst driving [18], but not many studies explored long-term effects in relation to screen disparity. And, where they do exist, their results are slightly contradictory; Pölönen et al. (2009) revealed very moderate visual discomfort after the cinema movie U2-3D [19], whereas Kuze and Ukai revealed significantly more visual discomfort after the movie 'Spy Kids: game over' in 3D than in 2D [20].

A relevant method to evaluate visual discomfort over time is to request viewers to assess the content continuously. This evaluation method requires participants to provide a real-time subjective rating of visual discomfort, using a slider or dial, from which the position is sampled at a fairly high frequency (e.g., 1–10 Hz) [21]. The advantage of this evaluation method is that this continuous set of ratings can be correlated to specific content characteristics that are known to be related to the pertinent determinants of visual discomfort. Fitting the continuous assessment scores of visual discomfort to these time-varying video content characteristics provides more information on the impact of these pertinent determinants. The disadvantage of this evaluation method is that the duration of the assessment should be limited to a maximum of 30 min as stated within the ITU-recommendations [22]. This is due to the possibility of strong visual fatigue caused by the assessment task itself. Since we also believe that concentration loss and mental fatigue might start to have an impact when assessing longer sequences, other assessment methods may be required for the perceived visual discomfort of e.g., feature-length 3D movies. In the current research we try to gain insight in how people experience visual discomfort while watching 3D movies and to which extent specific video characteristics induce visual discomfort in certain scenes.

1.1. Determinants of visual discomfort

To guarantee visual comfort in stereoscopic television, we recommend to adhere to the 'one degree of screen disparity' rule of thumb that determines a zone of comfortable viewing [13]. This still allows for satisfactory depth rendering for most application purposes. By applying this limit, excessive binocular parallax and the AC conflict do not seem to play a major role in being perceptually annoying. The tolerances in our fusion and AC systems are able to account for conflicts within one degree of screen disparity; fusion is possible and blur is not perceived. If viewers do not have some form of a binocular anomaly, stereoscopic viewing should be comfortable within this limit. 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 [13].

The first factor concerns 3D artifacts, which may result from insufficient depth information in the incoming data signal, yielding spatial and temporal inconsistencies [23]. After 2D-to-3D conversion and/or rendering, objects within the image are assigned incorrect screen disparity values based on motion estimation, assumptions, and heuristic cues [23]. The resulting 3D 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 [24]. Their presence and severity is directly related to (1) the amount of motion in the scene, which directly determines the visibility of 3D artifacts due to temporal inconsistencies and (2) the amount of screen disparity, i.e., allocation of objects to incorrect depth layers becomes more apparent and as such the impact of visual discomfort more severe with increasing screen disparity.

The second factor is excessive demand on AC linkage, which potentially can be caused by fast motion in depth and is expected to become more severe with prolonged viewing. The accommodative stimulus remains fixed on the screen, where the image is displayed sharpest, and the vergence stimulus may fluctuate in depth depending on the degree and the sign of screen disparity As a consequence an intrinsic mismatch arises within the AC linkage [25]. Though the mismatch should not result in a conflict within one degree of disparity, continuously stressing the linkage by objects with motion and changing screen disparity may exhaust the AC linkage and cause visual discomfort [13,14]. Yano et al. (2002) correlated continuous assessments of visual comfort with image characteristics per scene [14]. They detected a decline in accommodation response after watching the stereoscopic movies for approximately 1 h and revealed that scenes with rapidly moving objects and large screen disparities received low assessment scores in term of visual comfort. In line with these findings, one of their follow-up experiments confirmed that discrete changes of screen disparity in stereoscopic images resulted in a decline of accommodation response and in a significant decrease of visual comfort [26]. To further clarify the effect of changing screen disparity over time on visual discomfort, a relationship between the amount of screen disparity, object motion and visual comfort was verified [15]. In an experiment, participants assessed visual comfort of computer-generated objects that moved back and forth in depth periodically. 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 one degree limit.

The third factor is unnatural blur. The lack of blur, i.e., an entirely sharp image, can reduce the range of fusion, thereby hampering fusion of some displayed content. Additionally, it can strengthen the accommodation stimulus, which increases the mismatch between accommodation and vergence [27]. A surplus of blur can cause an ambiguous and unnatural depth percept. Additionally it can induce depth cue conflicts that yield visual discomfort [13,28]. In a worst-case scenario unnatural blur may facilitate or accelerate the development of accommodation difficulties or temporary nearsightedness [16]. The surplus of blur results from crosstalk [29]. Crosstalk is an artifact that results from the imperfect separation of the left and right eye's view, which may result in perceived ghosting or unnatural blur. Note that also 2D-to-3D conversion may induce similar perceptual effects, i.e., halos and unnatural blur. The presence and severity of unnatural blur, as well as its impact on visual discomfort, is also directly related to the amount of screen disparity [30].

1.2. Assessment methods

Subjective assessment methods as a means to perceptually evaluate stereoscopic as well as monoscopic content are nowadays widely accepted and applied. The Single Stimulus Quality Evaluation (SSQE) is proven to be a valid method to obtain a quality judgment of a single (still) stimulus, but also to obtain continuous time-varying judgments of moving sequences [21]. This latter method, referred to as Single Stimulus Continuous Quality Evaluation (SSCQE) is part of the ITU BT-500 recommendations [22], and is also mentioned in the ITU-R BT.1438, which specifically reflects on the evaluation of stereoscopic content [31]. The SSCQE was proposed by Hamberg and de Ridder to continuously evaluate the perceived quality of 2D video sequences, 20 min in duration [32]. IJsselsteijn, de Ridder, Hamberg, Bouwhuis and Freeman (1998) were the first to apply the SSCQE method to stereoscopic picture evaluation, continuously assessing presence, depth and natural-