Visual Discomfort Induced by Three-Dimensional Display Technology

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Abstract At present, three-dimensional (3D) display technology is attracting considerable attention. However, the added binocular depth introduced by stereoscopic 3D technology may not only provide viewers with an entirely different and enhanced viewing experience, but also with visual discomfort and visual fatigue. These problems, besides being related to the health and safety of viewers, have recently gained increasing attention because they significantly impede viewing experience. State-of-the-art studies on visual discomfort related to three-dimensional television (3DTV) are introduced. These studies include those on 3D display technology, the main causes of visual discomfort, subjective assessment measurement methods, and objective psychophysical prediction. This work is relevant to the industry as it suggest ways to prevent visual discomfort when producing 3D displays or shooting 3D videos.

Key words visual optics; three-dimensional display technology; visual discomfort; viewing experience; subjective assessment

OCIS codes 120.2040; 100.3005; 170.3880; 330.2210

三维显示技术引起的视觉疲劳研究综述

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摘要 三维(3D)显示技术正越来越吸引着人们的注意。3D显示中所增加的深度信息可以让人们增强体验感,但也会引发观测者的视觉不舒适和疲劳问题,极大地阻碍了3D显示技术在人们生活中的普及。由于3D显示技术引起的视觉不舒适和视觉疲劳关系到人们的健康安全问题,近年来大量学者对此进行了广泛而深入的研究。针对当今最先进的3D显示器技术引发的视觉不舒适的相关研究做一概括总结,包括3D显示技术、视觉疲劳的引发因素、对于视觉不舒适的主观测试方式以及仪器的预测方法。这对3D显示器、3D电视以及3D电影制造商具有参考价值。

关键词 视觉光学;三维显示技术;视觉不舒适;观测感受;主观测试

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1 Introduction

Human beings have depth perception, i.e., the visual ability to perceive the three-dimensional (3D) world. Depth perception arises from a variety of depth cues, such as binocular and monocular cues[1]. Binocular cues require inputs from both eyes, whereas monocular cues require input from one eye only. A 3D display utilizes the characteristics of the human visual system (HVS) on stereopsis perception. The human brain fuses left- and right-view images and then extracts relative depth information from retinal disparity, i.e., the distance between corresponding points in these images[2].

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Stereoscopic 3D (S- 3D) TV was first demonstrated by John Logie Baird in 1928[3] using the stereoscope invented by Charles Wheatstone in 1838[4]. During the 1950s, S-3D movies became popular in the United States. However, because the necessary technologies were still unavailable during that time, this 3D boom did not last long. With the current developments in hardware technologies, 3D movies have recently regained its popularity and consumers are demanding the same viewing experience in home entertainment through three-dimensional television (3DTV).

The added binocular depth introduced by S-3D technology provides viewers with an entirely different and enhanced viewing experience. However, this experience may also cause visual discomfort and visual fatigue. These issues have recently gained increasing attention because they do not only significantly impede the quality of experience (QoE) of viewers but also affect their health and safety. This paper reports on state-of-the-art studies on visual discomfort related to 3DTV, including those on 3D display technology, the main causes of visual discomfort, subjective assessment measurement methods, and objective psychophysical prediction.

2 3D display technology

2.1 Classification

A 3D display utilizes the characteristics of HVS on stereopsis perception[5]. The human brain fuses left- and right-view images and then extracts relative depth information from retinal disparity, i.e., the distance between corresponding points in these images[2]. This section introduces the classification of 3D displays and the standards set by the Society for Information Display.

The basic technique applied by 3D displays is to show offset images separately to the left and right eyes. The two sets of two-dimensional (2D) offset images are then combined in the brain to provide a perception of 3D depth. Two kinds of displays are generally available: stereoscopic and autostereoscopic. When using the former, viewers have to wear an optical device to direct left and right images to the appropriate eye. This technique is sometimes called aided viewing. In the latter, the technology that separates the two views is already integrated into the display. This technique is sometimes called free viewing. The distinguishing features of stereoscopic displays are as follows:

1) the method used to separate left- and right-eye views,

2) the implemented look-around capabilities (multiple views), and

3) the number of viewers who can simultaneously watch a stereoscopic sequence.

Stereoscopic displays with aided viewing (e.g., polarized glasses) are widely used and can either be time-parallel or time-sequential. In the former, left and right eye views are displayed simultaneously on one or two screens depending on the image separation technique used. The techniques used to direct distinct views to the appropriate eye in a time-parallel display system include the following:

1) location multiplexing,

2) anaglyph or color multiplexing, and

3) polarization multiplexing.

Another type of frequently used stereo display is based on the principle of time- sequential presentation, in which the left- and right-eye views of a stereo image is displayed in rapid alternation. The stereo pairs are viewed using synchronized active shuttering glasses that open alternately for the appropriate eye while closing the view of the other eye. This system exploits the HVS characteristic of integrating a stereo pair across a time lag of up to 50 ms[6].

Autostereoscopic displays that support free viewing (e.g., a 3DTV) are probably the best suited devices for such application. Wearing glasses in a home environment may be impractical and may limit the freedom of movement of viewers. The main categories of autostereoscopic displays are as follows: 1) direction-multiplexed, 2) volumetric, and 3) holographic displays. For additional details, refer to Ref.[7].

2.2 Performances

Given the different methods used in 3D display technologies for stereoscopic visualization, the performances of these technologies in terms of QoE vary. In Ref.[8], the angular characteristics of polarization-multiplexed and time-multiplexed 3D displays were studied. Based on evaluations viewing angle-related imperfections, i.e., crosstalk, brightness, and relative color saturation, time-multiplexed technology is better than polarization technology in terms of image quality and perceived depth. In Ref.[9], an LCD with polarized glasses, a plasma display with shutter glasses, and a projection system with shutter glasses were compared in terms of achievable viewing experience under different situations. The results showed that the performance of the studied display technologies are comparable in terms of 3D effect intensity, depth perception of a scene, and user involvement, but presented differences in terms of scene sharpness, visual comfort, and ambient light disturbance. In Ref.[10], the authors studied 2D display and different types of 3D display technologies and concluded that the performances of 2D and 3D displays significantly vary. In addition, among 3D display technologies, polarized display causes the least visual discomfort among viewers. In Ref.[11], the performances of autostereoscopic displays were investigated in terms of visual discomfort. Causes were also analyzed and improvement methods were proposed.

3 Main causes of visual discomfort

3.1 Definitions of binocular angular disparity

When displaying 3D images on flat-panel stereoscopic displays, the binocular angular disparity can be expressed by the visual angle degree[12] (Fig.1). L and R represent to left eye and right eye respectively, α is the visual angle at a fixed point on screen seen by two eyes, β is the visual angle at the corresponding 3D virtual object (ahead of screen) seen by two eyes, γ is the visual angle at the corresponding 3D virtual object (behind screen) seen by two eyes. The binocular angular disparities for points A and B, i.e., ϕ_A, ϕ_B, can be calculated by

$$\phi_A = \beta - \alpha, \tag{1}$$

$$\phi_B = \gamma - \alpha. \tag{2}$$

For a point on the screen plane, the binocular angular disparity is 0°, which indicates that no disparity occurs between two retinal images. A positive value represents crossed disparity, such as point A, whereas a negative value denotes uncrossed disparity, such as point B.

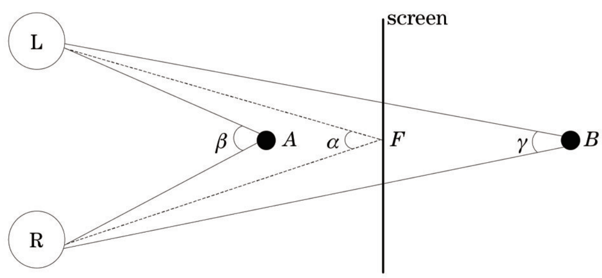


Fig.1 Definition of binocular angular disparity, where F is the fixation point

3.2 Vergence-accommodation conflict

The vergence-accommodation conflict is a well-known factor that induces visual discomfort[13-14]. When viewing an object on a 3D screen, the eyes converge to the virtual object that is in front of or behind the screen plane. However, accommodation has to be performed at screen depth level, which is unnatural and will not occur in normally. As this discrepancy between vergence and accommodation increases, the possibility that observers will experience visual discomfort also increases.

Numerous studies have been conducted to define the threshold of this discrepancy and determine the conditions in which viewers may not experience visual discomfort, i.e., the comfortable viewing zone. Yano *et al.*[15] proposed that the depth of field (DOF), which refers to the range of distances in image space within which an image appears in sharp focus, can be used to define the comfortable viewing zone in terms of diopters (D). A value of ±0.2 D is suggested[16-17]. Another definition of comfortable viewing zone was based on the results of empirical measurements, in which the ±1 rad of the visual angle was used[18-19]. Considering screen parallax, the comfortable viewing zone can be defined by a percentage of the horizontal screen size. For 3DTV, the value of ±3% is suggested[20]. For cinema, the suggested values are 1% for crossed and 2% for uncrossed disparities[21]. A comparison among these definitions is shown in Fig.2. In general, these definitions generate a similar comfortable viewing area. When shooting or producing a video content, 3D movie designers and producers should avoid values beyond the comfortable viewing zone. If an immersive or "shocking" effect is expected, then the duration of this part should be reduced.

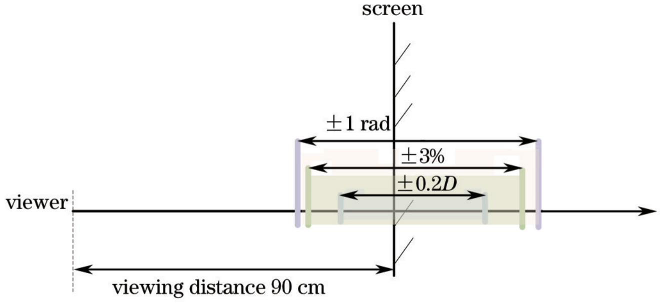


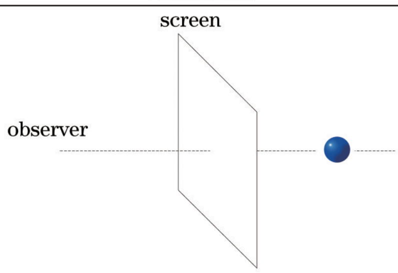
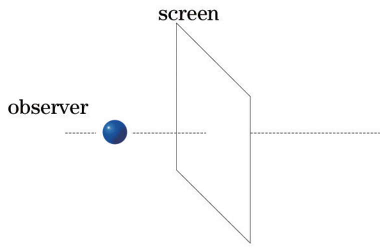
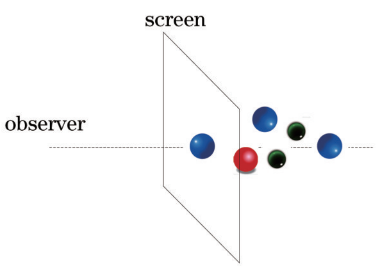
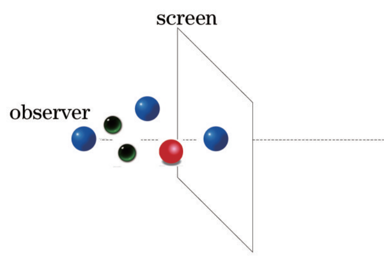
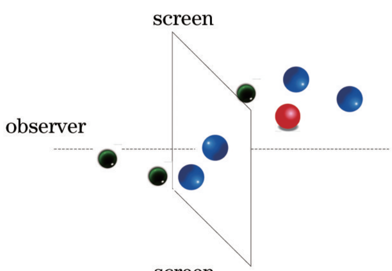
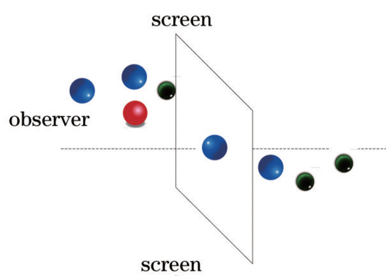
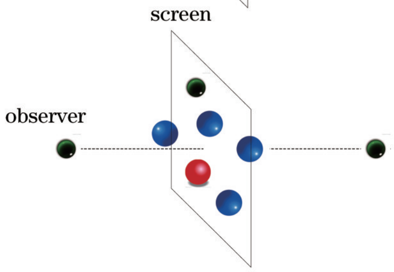
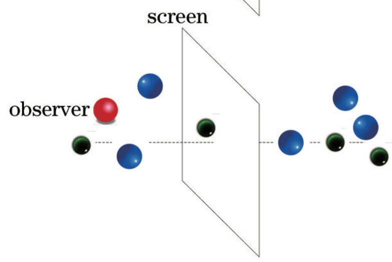
Fig.2 Comparison among different definitions of comfortable viewing distance [assuming that the screen size is 23 inch (1 inch=25.4 mm) and the viewing distance is 90 cm]

A large disparity induces a large vergence-accommodation conflict. In Ref.[10], the authors determined that the relationship between disparity and visual discomfort exhibits an s-type of growth, i.e., as disparity increases, visual discomfort or visual fatigue flatly increases at the beginning and then rapidly rises.

3.3 Parallax distribution

Aside from the large disparity magnitude, studies have shown that parallax distribution may also introduce visual discomfort[22-26]. A diagram is illustrated in Table 1. In this table, condition A causes less

Table 1 Different types of parallax distribution

	Condition A	Condition B
Excessive disparity		
Disparity skewness		
Disparity distribution of the top and bottom of the image		
Disparity dispersion		

visual discomfort than condition B.

1) Excessive uncrossed disparity (behind the screen) induces less visual discomfort compared with crossed disparity (in front of the screen) when the disparity magnitude is the same.

2) When the overall image is positioned behind the screen, visual discomfort will be less compared with when the image is placed in front of the screen.

3) If the image is split into top and bottom parts, then the stereoscopic image is more comfortable to watch when the parallax distribution on the top part is behind the screen and that on the bottom part is in front of the screen.

4) The dispersion of the disparity distribution should be small.

3.4 Binocular distortions

Binocular distortions or binocular image asymmetries seriously reduce visual comfort if they are present at a certain extent[27]. Asymmetries can be classified into optics related errors, filter related errors, and display related errors. Optics related errors are mainly geometric differences between left and right images, e.g., size inconsistency, vertical shift, rotation error, magnification, or reduced resolution. These errors typically occur when shooting or displaying stereoscopic images/videos. Filter related errors are mainly photometric differences between two views, e.g., color, sharpness, and contrast. The main source of error that is induced by a display system is crosstalk, which produces double contours and is a potential cause of discomfort[28]. A study showed that vertical disparity, crosstalk, and blur are the most dominant factors compared with other binocular factors in visual comfort[27].

3.5 Motion

Motion in 3DTV can be classified into planar (or lateral) motion and in-depth motion. In the former, the object only moves in a plane with a certain depth that is perpendicular to the observer while the disparity does not change temporally. Meanwhile, in-depth motion, also called motion in depth or z-motion, is defined as the movement of an object toward or away from an observer[29]. For planar motion, both eyes make the same conjunctive movements (called version)[30]. For in-depth motion, the eyes make opposite, disjunctive eye movements (called vergence)[31]. Fig.3 provides examples of planar motion and in-depth motion conditions. The speed of planar motion and in-depth motion can be expressed by the change in distance per second or the change in visual angle (version or vergence) per second.

In-depth motion is one of the significant factors that may cause visual discomfort. Studies have shown that visual discomfort increases with in-depth motion velocity[17,19-20,30,32]. However, the influence resulting from the disparity amplitude (disparity range) and disparity type (crossed or uncrossed) of in-depth motion on visual discomfort is still being investigated. In Ref.[19], the results showed that the disparity amplitude of a moving object is not a main factor. In Ref.[20], however, visual discomfort was shown to increase with disparity amplitude. Furthermore, the results also revealed that in-depth motion with crossed disparity induces significantly more visual discomfort than the uncrossed and mixed conditions. In Ref.[32], only the in-depth motion within the disparity range of $\pm 1°$ with different velocities was analyzed; hence, no conclusion was drawn regarding the influence of crossed or uncrossed disparity amplitude on visual discomfort.

The influence of planar motion on visual discomfort has also been studied[20,32-34]. These studies are highly consistent with the conclusion that visual discomfort increases with motion velocity. However, the influence of disparity on visual discomfort has led to different conclusions in these studies. In Ref.[32], the results indicated that disparity type, i.e., crossed and uncrossed disparities, did not affect visual discomfort thresholds. In Ref.[20], however, the results showed that crossed disparity causes more visual discomfort than uncrossed disparity. A possible explanation for this inconsistency is the position of the background. In Ref.[32], the background was positioned at the screen plane. In Ref.[20], the position of the background was not depicted. In Ref.[19], the background was positioned at a fixed place with the disparity of $-2.6°$. Therefore, the effect of background position on visual discomfort requires further study.

Most of the aforementioned studies investigated the influence of in-depth motion and planar motion on visual discomfort separately. To quantify the influences of static, planar, and in-depth motions, directly comparing their effects on visual discomfort is important. Thus, in Ref.[35], the visual discomfort induced by static, planar, and in-depth motions were compared under different disparity and velocity levels. The results indicated that for all three motion types, the relative disparity between the foreground and the background is a main factor in visual discomfort, i.e., visual discomfort increases with relative disparity. The gradient of visual discomfort with relative disparity is the highest for the static stimuli, followed by the in-depth, and then, the planar motion stimuli. This finding implies that static stimuli induce more visual discomfort when relative disparity exceeds a certain value, which is approximately 1.4° for planar motion and 2.05° for in-depth motion. In-depth motion stimuli are always more uncomfortable than planar motion stimuli in this previous study. However, when the disparity offset is less than 0.65°, we can extrapolate that slow in-depth motion stimuli may generate less visual discomfort than fast planar motion stimuli. Nevertheless, further studies are required.

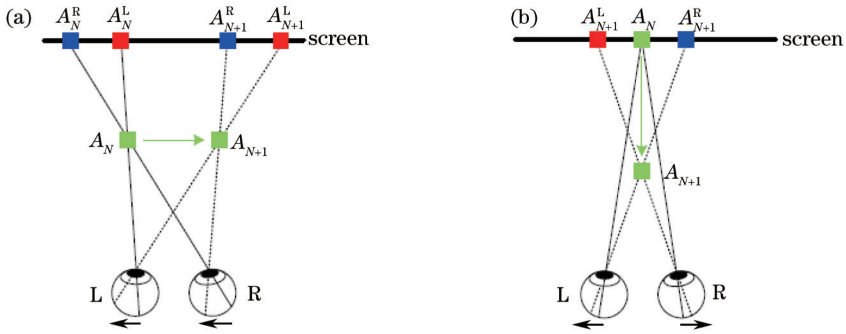


Fig.3 (a) Eye movement for planar motion; (b) eye movement for in-depth motion (A_N represents the perceived virtual object at frame N. A_N^L and A_N^R represent left-and right-view images, respectively, at frame N)

4 Subjective measurement methods

In ITU-R BT.2021[36], four assessment methods, which are subsets of the methods from Recommendation ITU-R BT.500[37], are suggested for measuring visual discomfort. These methods are as follows:

1) the single-stimulus(SS) method,

2) the double-stimulus continuous quality scale (DSCQS) method,

3) the stimulus-comparison (SC) method, and

4) the single-stimulus continuous quality evaluation (SSCQE) method.

Compared with the traditional 2D quality assessment scale labels, the labels for visual discomfort are slightly different, i.e., the discrete five-grade scale or continuous comfort scale labels are as follows: "Very comfortable", "Comfortable", "Mildly uncomfortable", "Uncomfortable", and "Extremely uncomfortable".

These methods have been widely used in the field. For example, in Ref.[15], the SSCQE method was used because it can measure the influence of duration on visual discomfort or visual fatigue. In Ref.[19-20,38-39], the authors used the SS method with a five-grade scale because of its simplicity and reliability. However, pairwise comparison has been recently accepted as a more reliable subjective assessment method for visual discomfort or QoE in 3DTV because viewers are not used to 3D conditions and are more accustomed to watching 2DTV. Thus, viewers may find it difficult to make judgments using a numerical scale (i.e., SS, DSCQS) given that they will have no reference. Pairwise comparison provides viewers with an opportunity to judge each pair by answering the following question: which one is more comfortable? Thus, scale issues are avoided and the results are more reliable. To increase the feasibility of pairwise comparison, Li *et al.*[40-41] proposed several designs to reduce the time complexity of the pairwise comparison method and increase its robustness to observation errors in tests. The proposed methods have been accepted by the IEEE P3333.1 Work Group[42] as the standard for 3DTV subjective assessment methodology. In July 2014, the Video Quality Expert Group (VQEG) established a test plan of the ground truth database for 3D video subjective assessment methodology. The pairwise comparison method will be employed in this database and a subjective experiment will be collaboratively conducted by different laboratories.

A questionnaire is another popular measurement tool. The simulator sickness questionnaire (SSQ) is a well-known and well-established questionnaire used to evaluate motion sickness caused by moving images[43]. The test items in SSQ include the following: "General discomfort", "Fatigue", "Headache", "Eye strain", "Difficulty focusing", "Blurred vision", etc. Participants are asked to fill in the questionnaire item by item and select an answer from "None", "Slight", "Moderate", and "Severe". Ohno *et al.*[44] developed their own questionnaire based on SSQ and the "List of Symptoms of Visual Fatigue" from Ref.[45]. In Ref.[18], the authors developed a new questionnaire to subjectively assess visual fatigue caused by viewing various types of moving images.

5 Objective physchophysical prediction

Aside from subjective assessment methods, visual discomfort or visual fatigue induced by 3DTV may be predicted or measured using objective psychophysical devices. For example, electroencephalography (EEG) and functional magnetic resonance imaging have been used to assess brain activities that are related to the processing of and the reactions to stimuli (e.g., emotion and visual fatigue). In Ref.[46], an EEG device was used to compare brain activities when watching 2D and 3D video sequences. The results showed that the power of the EEG signals in beta frequency (14 Hz~25 Hz) was significantly higher when watching 3D contents, which may be related to either visual discomfort or visual fatigue. In Ref.[47], the authors studied the feasibility of using EEG to detect visual discomfort, and they found that "the spectral attenuation of alpha and beta bands over the sensorimotor area and the temporal features detected 2 to 4 seconds after the onset can be strong indicators of visual discomfort". An example of using EEG (at the consumer level) in a psychophysical experiment is shown in Fig.4.

Fig.4 Example of using EEG (at the consumer level) to conduct psychophysical experiment

Electromyography (EMG) and electrooculography are used to detect activities related to the eyes,e.g., electrical activities produced by the skeletal muscles of the eyes and eye movements, which are considered as indicators of visual fatigue. Furthermore, eye blinking rate may change under different viewing conditions, which can be used to predict visual discomfort or visual fatigue. Studies have shown that under relaxed conditions, people will blink more frequently than when they are reading a book or working on a computer[48]. In Ref.[49−50], the results showed that blinking rate is higher when watching a 3D video than a 2D video. In Ref.[51], a conclusion was drawn that eye blinking rate increases with visual fatigue when watching 3D images. For conditions that use display screens, blinking frequency is significantly decreased when fatigue is reported (e.g., reading information from the screen for a long time)[52]. In Ref.[53], the authors studied the relationship between eye blinking rate and different types of

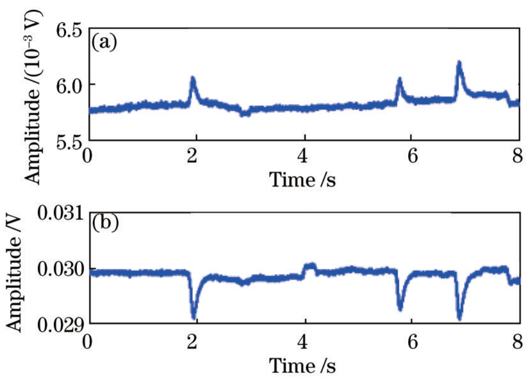


Fig.5 Example of EMG signals for the (a) top and (b) bottom eyelids of the left eye, where the eye blinking signal can be detected

3D motion. An example of an eye blinking signal is shown in Fig.5. The results indicated that velocity in 3D videos is a main factor in eye blinking, and that its effect on eye blinking is significantly different for planar motion stimuli and in-depth motion stimuli. Eye blinking frequency decreases with increasing motion velocity for planar motion stimuli but increases for in-depth motion stimuli. The results also showed that the relationship between eye blinking rate and visual discomfort is nearly linear. For static and in-depth motion stimuli, the frequency of eye blinking increases with visual discomfort. By contrast, blinking rate decreases with increasing visual discomfort for planar motion stimuli. In conclusion, eye blinking performs differently under varying conditions, e.g., relaxed, reading, long-term viewing of displays, and watching 2D and 3D images.

6 Conclusion

Visual discomfort is an important issue in developing and applying 3D display technology. State-of-the-art studies on visual discomfort, including those on basic knowledge on 3D display technology, possible factors that may induce visual discomfort, and assessing visual discomfort using subjective methods and objective psychophysical devices are reported.

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