We suggest a rule of thumb for comfortably viewing stereoscopic displays, and also highlight circumstances under which visual comfort may be compromised.

Introduction

If three-dimensional television (3D-TV) and its desktop counterpart for 3D gaming are to be successful, visual comfort must at least be comparable to conventional display standards. Technical choices and compromises made throughout the entire chain of stereoscopic image generation, transmission, rendering, and display can affect the overall visual comfort experienced by the viewer. In fact, visual discomfort associated with stereoscopic displays is often cited as one of the main barriers to rapid diffusion and customer acceptance of this technology in the marketplace.

Numerous human factors studies have looked at elements of the stereoscopic imaging chain to assess and quantify their impact on visual comfort. Introduction of new stereoscopic data formats (e.g., RGB + depth), as well as increased commercialization of stereoscopic displays in both home and professional markets, motivated this in-depth review of empirical studies focused on visual comfort. Our aim is to assess the current state of the art, formulate criteria and scope conditions for visual comfort, and identify potential areas that could benefit from further study.

Although visual discomfort is often regarded as a serious health concern associated with displays, it appears to be a somewhat ambiguous concept, with numerous and widespread causes, symptoms, and associated indicators. Moreover, it is often used interchangeably with the notion of visual fatigue. We define visual fatigue as a decrease in performance of the visual system, measured through, for example, the speed of accommodation of the eyes’ lenses. As such, it is an objectively measurable criterion that is of particular value for ascertaining long-term adaptive processes of the visual system. However, to distinguish clinically significant visual fatigue from unproblematic, functional adaptations of the visual system, we need to incorporate a measure of subjective visual discomfort: to what extent objective visual changes associated with particular complaints?

Factors underlying visual discomfort

In most studies, visual discomfort is defined according to a combination of underlying factors and symptoms. Four main causes of visual discomfort are attributed to stereoscopic displays, i.e., anomalies of binocular vision, binocular asymmetries, accommodation-convergence mismatch (AC mismatch), and excessive binocular disparity. Anomalies of the human visual system that affect visual comfort have been well documented in the ophthalmologic literature, and affect only a relatively small number of viewers. The effects of various binocular asymmetries, based either on asymmetrical optical geometry (e.g., image shift, rotation, magnification) or filter characteristics (e.g., luminance, contrast, color differences, cross-talk), have been studied extensively, and reviews are available elsewhere.\textsuperscript{1,2}

Our current work, presented at the most recent SPIE 2007 conference on Stereoscopic Displays and Applications, focuses on AC mismatch and excessive binocular disparity. Both factors impose limiting conditions on the amount of depth that can be comfortably induced on a stereoscopic display. AC mismatch arises from an intrinsic conflict between the accommodative stimulus,
which remains fixed on the stereoscopic screen, and the vergence stimulus, which may fluctuate in depth. Since accommodation and vergence are reflexively coupled mechanisms (stimulation of one system will produce a response in both), their artificial decoupling when viewing stereoscopic displays has often been posited as a significant factor underlying the occurrence of visual discomfort. Similarly, the human visual system has natural limits to its ability to fuse images that contain binocular disparities, and introducing unnatural or excessive disparities elicits visual discomfort.

Toward a zone of comfortable viewing

We wish to determine a range of induced depth where visual discomfort is unlikely to occur. The depth of focus (DOF) of the human eye denotes a region where a certain level of mismatch between accommodation and vergence is tolerated. Similarly, there is a region around the fixation point where disparities can still be comfortably fused. Limits for DOF and binocular disparity of 0.3 diopter and 60 arcmin, respectively, are generally acknowledged, though somewhat lower recommendations have been reported as well. The disparity limit is related to the human eye’s aperture and depth of focus. Indeed, calculated in distances, the comfortable viewing zones for disparity and DOF show very high resemblance and can serve as a general limit.

Within this range, binocular fusion is possible and blur is not perceived. Hence, stereoscopic viewing should be comfortable. However, with certain stereoscopic image content, visual discomfort may still occur within this limit, and we believe three factors to be the most pertinent ones. The first is excessive demand of the accommodation-convergence linkage, which can be caused by fast motion in depth and is expected to become more severe with prolonged viewing and at short viewing distances. The second factor, 3D artifacts, results from insufficient depth information in the incoming data signal and yields spatial and temporal inconsistencies. It has not yet been subjected to much research, though inconsistencies, such as conflicts between different depth cues and geometrical distortions, have already proved to cause annoyance and visual discomfort. The third factor concerns unnatural amounts of blur, which may cause ambiguous and unnatural depth percepts. A surplus of blur resulting from cross-talk, 2D-to-3D conversion, and artificially induced DOF, brings about annoyance, visual discomfort, and depth cue conflicts. On the other hand, the lack of blur, i.e., an entirely sharp image, can reduce the range of fusion, thereby causing fusion difficulties and depth cue conflicts.

Conclusion

We have reviewed the concept of visual fatigue and its subjective counterpart, visual discomfort, in relation to stereoscopic display technology and image generation. To guarantee visual comfort in consumer applications, such as stereoscopic television, a general recommendation is to adhere to the ‘one degree of disparity’ rule of thumb, which still allows for sufficient depth rendering for most application purposes. Within this zone of comfortable viewing, visual discomfort may still occur to an extent, however, which is likely to be caused by one or more of the following three factors: excessive demand of accommodation-convergence linkage, e.g., by fast motion in depth, viewed at short distances; 3D artifacts resulting from insufficient depth information in the incoming data signal, yielding spatial and temporal inconsistencies; and unnatural amounts of blur. To adequately characterize and understand visual fatigue and visual discomfort, multiple types of measurements, both objective and subjective, are needed. This is the point of departure for our future endeavors in this area.

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