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Stereoscopy in Virtual Reality

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Abstract — *Virtual reality technologies with mobile head-mounted displays have come to grow in popularity. To enhance the sense of immersion in virtual environments, many applications use binocular screens and stereoscopy. The new devices have come to represent the additional applications and markets for stereoscopic content. Not only are there interactive virtual worlds that can be visualized in stereoscopic 3D, but it is also possible now to watch stereoscopic cinema movies using mobile headsets. However, 3D cinema and head-mounted displays deliver a considerably different visual experience of stereoscopy. This study compares the stereoscopic experiences of 3D head-mounted displays with those of 3D cinema and 3D television. It further reviews the recent stereoscopy trends found in mobile virtual reality headsets. This paper aims to help improve the quality of stereoscopic content by optimizing the artistic and technical differences. It has been found that improved content production can increase the acceptance and market potential of stereoscopic content in virtual reality.*

Keywords — *HMD, stereoscopy, virtual reality*

I. INTRODUCTION

Technological progress and quality improvements forecast a prosperous future for mobile virtual reality (VR) devices [1]. An example [2] of this is presented in Fig. 1. While smart glasses and head-mounted displays (HMD) have been in the market for decades, only the mobile devices of the latest generation have crossed the technical milestone. Standalone mobile headsets such as Quest2 or Hololens2 are the prototypes of new generation mobile devices, combining autonomous computing power with high-resolution display technology and new solutions to enhance the comfort and interactivity of viewers.

Progress can also be observed with there being an increasing amount of content and applications. Games are available on the manufacturers' platform and made available via standardized and open protocols and application programming interfaces (API) such as WebXR [3].

Increased viewing angles and high-resolution binocular displays with improved sound can fascinate users like never before [4]. A significant part of the new degree of realism is due to the comfortable stereoscopic visualization. Stereoscopy has become a standard feature while rendering most of the applications. Until recently, high-quality content could only be seen in 3D cinema or 3D television (3DTV). However, as the production of new 3D content appears to stagnate for these media [5], mobile HMD seems to have become the new market for stereoscopic applications.

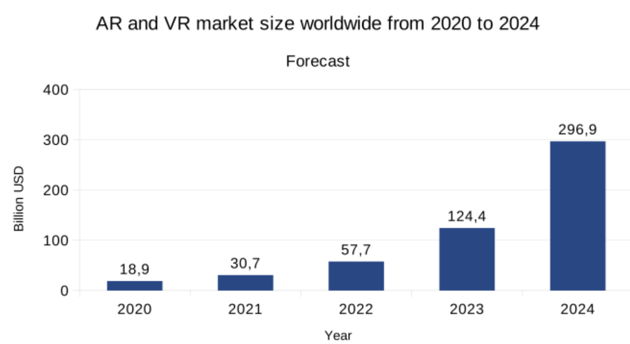

Fig 1. Market forecast for the years 2020 to 2024

While all forms of display technologies allow us to view stereoscopic 3D content, the visual impressions may vary considerably. Each of the devices has different features and constraints in ways that the same content is perceived differently. While 3D cinema and 3DTV have developed many artistic qualities over the years, mobile HMD VR devices are closely related to video games and their particular types of stereoscopy.

How are the stereoscopic visual impressions different in each of the media? What is important in the content creation process? Further, what are the consequences of the physiological differences of the devices and human factors on the quality of content?

This paper compares the use of stereoscopy in the new generation of mobile HMD devices with visualization experiences drawn from the traditional stereoscopic display devices.

II. MATERIALS AND METHODS

The research method adopted in this study is that of comparison. To compare the stereoscopy of three different display types, this research makes a few technical assumptions that describe the features and usage conditions of each of the media.

Table I presents a summary of the technical feature comparisons of the three media types. As a VR device, a headset with features similar to that of an Oculus Quest2 is assumed [6].

TABLE I
COMPARING THE TECHNICAL FEATURES OF HMD, 3DTV, AND 3D CINEMA

	HMD	3DTV	3D Cinema
Technical setup	Oculus Quest2	65-inch TV	SMPTE guide
Approximate image width	4.0 m	1.45 m	10 m
Field of view angle	90°	30°	43°
Approximate focus distance	2 m	2.43 m	13 m

The technical viewing angle of 90° in combination with a corrected focus distance of approximately 2 m can provide an image experience comparable to watching a 4 m large screen at that distance. The 3DTV is assumed to be a 65-inch model with an ideal viewing angle positioned at 30°; it brings the viewing and focus distance to approximately 2.43 m [7]. The 3D cinema contains numerous variables. Viewing experiences change with the screen size and seating position. For the case of simplicity, it is assumed that the screen is 10 m large and that the viewer sits on the best seat based on SMPTE [8] recommendations—a viewing angle of approximately 43° and a seating and focus distance of about 13 m.

Various improvements have been accomplished in VR interactivity, which is a distinct feature of mobile VR devices. Previous research was conducted on multiple methods in interaction with user interfaces [9]. However, as the comparison in this study focuses on stereoscopy, interactivity does not fall within the scope of this article.

The above assumptions describe three different devices and viewing situations, which are the basis of this comparative study.

III. RESULTS

The technical parameters described in Table I influence stereoscopy observed in different media. As human physiognomy can be considered as constant, different technical parameters and features influence stereoscopic viewing and content perception. To establish the principal differences concerning stereoscopic content from a cinematographic creator's perspective, the comparison will cover the influence of the following parameters and features:

- Limitations in-depth perception;
- Immersion;
- Screen plane;
- Camera focal length and convergence;
- Camera and viewer interaxial distance;

A. Limitations in-depth perception

The magnitude of stereoscopic depth perception is related to the viewing distance of a display. Stereoscopic content is usually created with respect to a zone of comfort to avoid eye strains and other discomforts. Shibata et al. discovered 2011 that this comfort zone is relatively small in a near viewing and increases with the viewing distance [10]. Owing to the larger viewing distances, 3D cinema allows the viewing of perceived infinity. Eyes focus and look in parallel when viewing the extremely far objects. As the focal distance is much closer, 3DTV and mobile VR devices do not display this amount of perceived depth. While these displays show the volume behind the screen and in front of the device, the far distances do not appear as infinity. Consequently, the stereoscopy in 3DTV and mobile VR can be considered with limited in-depth perception.

B. Immersion and screen plane

3D cinema and 3DTV cover a viewing angle of approximately 30-45°. Compared to the HMD with a 90° viewing angle, these are not fully immersive. Consequently, the frame around the image or the border of the cinema screen is within the field of vision. With regard to stereoscopic viewing, this frame has an important function. It is called screen plane, stereo window, or zero parallax plane [11]. When there is no parallax between the same object points on the left and the right image, the object appears to be positioned on the screen plane. When the parallax is positive, the point seems to appear behind the screen plane. When the parallax is negative, the point appears in the space between the screen plane and the eyes of the viewer. The screen plane creates a reference for a viewer to evaluate the relative position of the objects in space. The stereoscopy found in totally immersive VR devices does not have a visible screen plane. The viewing perception can be compared with the viewing of an IMAX screen [12]. The difference is the focus distance, which is far on a cinema screen and close in VR. The absence of screen plane reduces the number of depth cues for the estimation of distances in the viewing situation. The screen of a 3D display is like an imaginary plane that can be used to reference the position of objects in space. The stereoscopic image in mobile VR is an image without an image plane. It is a transplane image and has similarities with a hologram [13].

To reproduce the perception of a stereoscopic 3D movie on a screen, a VR device can simulate the viewing of a display or a large screen by positioning the stereoscopic content on a visible frame. The google cardboard viewer application enables the performance of this simulation, and most mobile VR devices enable the positioning of virtual windows in space. In previous research, several setups could be compared, and a viewing situation similar to that of a cinema screen showed the best results during test evaluation [14]. In the field of audio technology, this method would correspond to the creation of virtual speakers as imaginary sound sources found in an audio wave-field synthesis environment [15].

C. Camera focal length and convergence

The focal length of the camera used in various stereoscopic media is based on different paradigms. In 3D cinema and 3DTV, focal lengths are the result of the artistic choice of content creators. They are established tools for storytelling. In 3D cinema and 3D TV, focal lengths are variable. In television sports especially, the application of zoom lenses is extremely popular. Sophisticated solutions have been developed by multiple manufacturers to ease the constraints of stereoscopic productions.

In games, most of the game engines allow a parametric control of stereoscopy. Special software development kits (SDKs) such as Trioviz are particularly designed to deliver constant stereoscopic quality images on multiple non-immersive displays [7].

Mobile VR seems to aim for a naturalistic reproduction of artificial spaces [16]. As the human visual system does not allow for a change in focal length, the changes in focal length are usually not desired and can be disturbing. The application of focal length in mobile VR can thus be considered as static when compared to 3DTV and 3D cinema.

Camera convergence is a considerably specific parameter and is equivalent to horizontal image translation in stereoscopic media production. This parameter has the principal function of being able to adjust the parallax in images [17]. This can be used to control the depth in an image and adjust the screen plane. This parameter is technically and artistically variable in 3DTV and 3D cinema. As mobile VR lacks a screen plane as a result of full immersion, convergence appears static and is comparable to the parameter of focal length. It can be used to increase viewing comfort.

D. Camera and viewer interaxial

The interaxial distance in a 3D movie or 3DTV is generally variable to match the constraints of focal length, parallax, and screen plane. However, an important variation in the interaxial distance can alter the impression of the size of objects and can make a scene appear larger or smaller than it really is [18]. To render the most naturalistic perception of a scene, mobile VR generally positions the camera in an interaxial static angle.

While the camera interaxial distance can vary in 3DTV and 3D cinema, in mobile VR, it is the viewer interaxial that can be changed. In the first generation of google card board applications, the viewer setup involved a complex setup and calibration process. For this purpose, Google created a dedicated application: the cardboard viewer profile generator [19]. Interocular distances and manufacturers' dimensions were all aggregated in a data set. Encoded as barcoded, they could be printed on the side of the cardboard device. The corresponding viewer application could read these calibration codes and adjust the playback and display of the content to best match the display of the user. Mobile VR devices such as the Oculus Quest2 allow for mechanically adjusting the position of the displays in the eyepiece to ensure individual accuracy and comfort.

TABLE II
SUMMARY STEREOSCOPIC COMPARISONS OF HMD, 3DTV, AND 3D CINEMA

	HMD	3DTV	3D Cinema
Depth perception	Limited	Limited	Infinity
Screen plane	None	2.43 m	13 m
Immersive	Yes	No	No
Camera focal length	Static	Variable	Variable
Camera convergence	Static	Variable	Variable
Camera interaxial distance	Static	Variable	Variable
Viewer interaxial distance	Variable	Static	Static

IV. DISCUSSION

A. Overcoming the vergence-accommodation conflict

Users of stereoscopic applications have often suffered from discomfort and visual fatigue. Many studies have been conducted to investigate the origins of these phenomena [20], [21]. One of the principal reasons lies in the fact that natural binocular vision is different from the vision on stereoscopic displays. In natural vision situations, viewers focus on a certain object and then move their eyeballs to converge on the object. Owing to the combination of two depth cues—vergence and accommodation—the human visual system can visualize objects in space and evaluate distances. When watching a stereoscopic screen, however, these two depth cues can be dissociated. While the viewers' eyes keep focusing on the screen, vergence follows the imaginary objects in front of or behind the screen. Fig. 2 illustrates the two different viewing situations. The amount of discomfort created by the dissociation of accommodation and vergence is not constant. Shibata et al. revealed in their research that disparities are less comfortable the closer they move toward the eyes [10]. Consequently, the zone of comfort for stereoscopic viewing is small in the near range and expands toward infinity. This phenomenon explains why the small mobile devices used close to a viewer usually only allow for a considerably reduced depth, while large depth impressions can prevail comfortably in 3D cinemas.

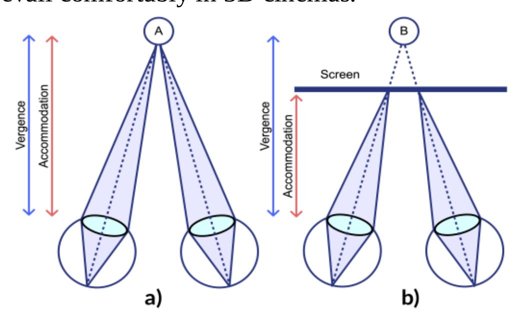

Fig. 2. Vergence-Accommodation conflict: a) Natural view; b) Screen view

B. Cinematographic depth

Depth in cinema is often discussed as an artistic issue. Classical cinema being mostly two-dimensional and flat entails several techniques used to create the impression of depth. Similar to other arts such as paintings, cinematographers utilize monocular depth cues such as occlusion, size, shadow, areal perspective, and depth of field [22]. The last two are often artistically applied by photographic lenses. Since the beginning of cinematography, lenses fall within the basic artistic tools bracket. They are used by cinematographers to interpret and transform the space and depth they record. Fig. 3 presents an example of how focal lengths influence the proportions in space.

The figure compares two camera setups: one lens (P) with a normal focal length (f1) and the other lens with a greater focal length (f2). Each lens setup contains two objects (A and B) of identical height and are at a given distance (Δd). The right side of the figure shows the film plane with the projected object images (A'1 and B'1 for f1 and A'2 and B'2 for f2). As opposed to the features of the human viewing system where the focal length and interocular distance are invariable, cinematography technically allows for the modification of these features. Consequently, the size of the objects in relation to each other can be visually affected. The longer focal lens allows one to film from a longer distance and appears to compress the space. The same objects at a closer distance and shorter focal length appear differently: objects closer to the lens appear relatively larger in comparison to the same sized far objects. This setup can create the felling of a stretched and a more empty space. Cinematographers frequently use this effect for storytelling purposes.

In the stereoscopy used in 3D cinema and 3DTV, binocular depth cues such as disparity add to the perception of depth. This affects not only the proportions of the objects in relation to each other but also the volume of the objects themselves. Volumetric distortion levels in stereoscopy are often referred to as roundness [23]. As the proportions of the foreground and background are modified by lenses, stereoscopy often recurs to the variation of interaxial distances to maintain the parallaxes within a comfortable distance.

Stereoscopy in VR generally works with a fixed visual setup. Most content uses focal lengths like that of the human vision system. The major objective does not seem to be an interpretation or modification of the space following a narration but an illusion of realistic immersion in an imaginary virtual world. Experimental research has been conducted to create immersive VR using long focal lenses [24]. The results show difficulties with life action images owing to the positioning in space, and computer-generated images would equally require new content creation approaches.

While the transformation of spaces has become a part of the illusion of cinematographic continuity, it seems that VR avoids any alternations that disturb the continuity of the visual experience.

Consequently, the two major differences of cinematographic depth and depth in virtual reality applications can be observed; VR stereoscopy imitates a vision system similar to that of natural vision. It tends to avoid all technical and artistic features that are likely to disrupt the continuity of space and time during the experience.

Many VR applications are game based, and they often recur to cinematographic like aesthetics in two-dimensional spaces [25]. VR seems to prefer a naturalistic vision approach at the moment.

Looking back at the historical development of digital stereoscopy, similar carefulness could be observed in the initial 3D cinema productions. After a decade, 3D cinema has come to overcome many technical difficulties and uses optics variation as an integral part of its storytelling. Table II summarizes the principal results of this comparison.

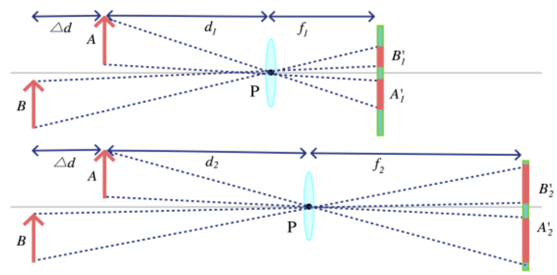

Fig. 3. Focal lenses and projection image proportions

V. CONCLUSIONS

This paper compared the differences in the stereoscopy of different display media: mobile VR HMDs, 3DTV, and 3D cinema. While all the devices can display stereoscopic content in principle, the application and perception are considerably different for each of them.

With the viewing angles ranging between 30 and 45 degrees, 3DTV and 3D cinema are not immersive. The image frame is visible and is a part of the stereoscopic image as a screen plane. Its borders allow for the positioning of objects in space with relative positions before and behind the screen. In addition, the different focal lengths can modify the proportions in space, and the variation of interaxial camera distances can change the perception of object sizes. This set of parameters enables the content creators to use stereoscopy in artistic storytelling.

Stereoscopy in mobile VR headsets seems to follow a different paradigm. As a naturalistic image perception is intended, any parameter that can disrupt the continuity of time and space are avoided. Most of the parameters that are variables in 3DTV and 3D cinema are constants in VR.

The usage of stereoscopy in mobile VR headsets is thus considerably different from the stereoscopy in 3D cinema and 3DTV and is not ready to be directly transferred from one to another. Mobile VR headsets can simulate cinematographic stereoscopic viewing experience indirectly by displaying virtual screens on devices that can show stereoscopic contents. Consequently, the contents are required to be designed and adapted properly for the medium for which they are intended.

The users of mobile VR headsets can benefit if the media producers optimize their content for the different display devices. Improvements in content quality could help raise the acceptance of mobile VR devices and increase the market for higher quality stereoscopic content.

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