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Consumer-oriented Head Mounted Displays: analysis and evaluation of stereoscopic characteristics and user preferences

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Abstract The increasing availability of advanced but affordable technologies is providing interesting opportunities for the development of ICT applications for the social good. In particolar, the upcoming diffusion of advanced Head Mounted Displays dedicated to the consumer market has lead to a great interest in the design and production of dedicated media, like e.g. immersive movies and Virtual Reality applications. These devices use stereoscopic visualization to enhance the sense of realism and immersivity in a virtual scene. However, a correct stereoscopic visualization requires an accurate consideration of different parameters related to the production and display stages. In this paper, we analyze the stereoscopic setup of a Head Mounted Display, in order to highlight its main visualization characteristics in relation with the known issues and requirements for a correct stereoscopic visualization, and to establish some preliminary guidelines for an optimal creation of stereoscopic contents.

Keywords Head Mounted Display · HMD · Oculus Rift · Stereoscopy · Stereoscopic media production · Stereo Window Violation · 360° movies · Social good

1 Introduction

The large and increasing diffusion of mobile and smart technologies, together with the popularity of social networks, is providing interesting opportunities for the development of ICT applications for the *social good*, in all its different meanings. In addition to the possible improvements in our everyday life, one of the most crucial aspects of this research field is that, due to the growing availability of ICT technologies around the world, these innovative applications are becoming available also in remote areas of the world, allowing to marginalized populations the access to different life-improving services, overcoming existing infrastructural and economical barriers.

From an ICT point of view, the topic can be approached in several different ways. In the last years, different researches have been proposed on the implementation of video game-based applications and technologies for different aspects of the social good field. Some works have investigated e.g., the design of proximity-based games aimed at fostering the use of the public transportation systems [1,2], the implementation of a serious game to create awareness on cardiopulmonary resuscitation maneuvers [3,4], and the effect of video games as a technological support for the rehabilitation of seniors [5] and for the assistance of children with cognitive [6] or hearing [7] impairments. Moreover, with the upcoming interest for online 3D interactive environments, particular efforts have been made in order to address the issues related to the development of complex online collaborative applications [8], and to the management of the huge amount of dynamic information generated by online communities and social networks [9].

Recently, there is a relevant interest in the consideration of Virtual Reality (VR) visualization and interaction technologies [10–12] in the social good field. VR has been one of the most investigated research topics of the last 50 years, and several applications have already been proposed for socially relevant fields like industrial research (e.g., for the training of personnel involved in critical situations in dangerous environments [13]), medicine (due to the advanced visualization and

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simulation capabilities [14]), or perceptual psychology (in order to replicate realistic situations in a controlled virtual setup [15]). Most of these VR applications were based on high-level, expensive devices, and therefore their diffusion was limited only to advanced research centers. However, a new generation of VR devices is becoming increasingly more available. These new devices are assembled using high quality electronic components (in particular displays and sensors) already available for the manufacturing of mobile or portable devices, with a price range actually lower than the specialized VR devices used before. The target of these devices is mainly the consumer market for entertainment, which is currently focused on the definition of an integrated "ecosystem" of portable devices and smart objects.

In particular, different models of affordable Head Mounted Displays (HMDs) have been proposed in the last months, like e.g., Oculus Rift, HTC Vive, Playstation VR, Samsung Gear VR, Google Cardboard. HMDs have always been largely used and studied in the VR field: due to the technological limits of the HMD models available until some years ago, one of the most discussed research topics has been the evaluation of their appropriateness in presenting stereoscopic information [16]. In fact, their limited Field of View (FOV) has often been considered one possible reason of the relevated underestimation of depth and distances in VR environments [17,18], even if other works [19,20] have suggested that this effect can be mitigated if the user can look around the environment without constraints. However, the more recent HMD models are characterized by lower latency, higher resolution displays, and larger FOV than the previous generation of devices. Moreover, some portable HMDs are even using smartphones as the main processing and visualization units, allowing an easier use, a larger diffusion, and an efficient integration between VR and mobile technologies and applications.

As a consequence, there is a growing interest in the production of dedicated media (like e.g., immersive video games, and 360° stereoscopic movies) specifically designed to exploit the peculiar characteristics of HMDs, and the strong potentialities of VR as a powerful communication process [21,22]. Examples of immersive VR content in the social good field are focused on innovative environmental awareness [23] and humanitarian [24] campaigns, and on the diffusion of educational material aimed at providing realistic simulations [25] and engaging environments [26]. Moreover, the use of immersive stereoscopic movies is also creating new paradigms in journalism [27], by the proposition of news based on a first person experience, in order to create a deeper connection with the audience.

Therefore, the production and visualization of stereoscopic media is of crucial importance for the success and effectiveness of the aformentioned innovative methodologies aimed at enhancing our everyday life, and at providing a positive effect in many different sensibilization campaigns and social activities. However, stereoscopic production requires an accurate knowledge of all the aspects related to the acquisition/generation setup, and of the visualization parameters of the 3D display, in order to obtain an optimal representation of depth, and to avoid annoying perceptual issues like e.g., excessive parallax on screen, or window violations [28,29], which can affect the success in a large diffusion and fruition of the contents.

In this paper, we will present an analysis of the stereoscopic setup of a consumer-oriented HMD, in order to understand its visualization characteristics and stereoscopic performances, and to determine some guidelines for an optimal creation of stereoscopic contents. Moreover, to better evaluate the technical peculiarities of these devices, we will present a comparison of the stereo parameters of the considered HMD with the visualization setup typical of a 3D monitor. A preliminary version of the presented analysis has been described in [30].

The remainder of this paper is organised as follows. In Section 2, we present a brief introduction of stereoscopy and of some crucial parameters to consider for a correct production of stereoscopic content. In Section 3 we analyze the stereoscopic characteristics of a HMD and we compare them with a visualization setup based on a 3D monitor. In Section 4, we present the result of an experimental session, performed with 20 users, aimed at analyzing the possible differences in the observers' feedback using the two different visualization setups. We conclude the paper with a final discussion in Section 5.

2 Stereoscopic parameters for correct content production

In the last few years, several solutions for the acquisition, elaboration, and visualization of stereoscopic movies [28,29,31] and video games [32–34] have been proposed.

Stereoscopic visualization is used to create an illusion of depth in the observer, by means of two images corresponding to two different perspective views of a scene. These two images are each sent only to the left or right eye of the viewer using specific hardware solutions. If the observer has an adequate stereoscopic ability [35], her visual system processes the binocular disparity between the two views (i.e., the horizontal different positions of an object in the two images), elaborating the perception of depth.

The production of a correct stereoscopic content is a complex task which requires an accurate comprehension of all the parameters and settings of both the acquisition and visualization setups. The main goal is usually to achieve a spectacular representation of virtual depth while avoiding perceptual discomfort in the observer. In this paper, we focus our analysis of the stereoscopic characteristics of a HMD on three crucial parameters: the *native parallax* of the display, the *maximum positive parallax* on screen, and the presence of *window violations* in a stereoscopic setup.

Native screen parallax NP

The native screen parallax NP is a parameter describing the stereoscopic characteristics of a 3D display, independently from the settings regarding the acquisition and visualization of the stereo content [28]. It is calculated as:

$$NP = \frac{iod}{sw} \tag{1}$$

where iod is the human interocular distance (approximately 2.56 in/65 mm), and sw is the screen width. NP can be interpreted as the percentage of screen width which will equal the human interocular distance; i.e., the maximum amount of pixel disparity on screen before having a painful *divergent parallax* situation [36].

Maximum parallax on screen MPP

One of the main source of discomfort in an observer is an excessive positive parallax on screen, which makes the process of fusion of the two views difficult, if not impossible, to the viewer. For a given 3D display, the native parallax NP gives the parallax threshold before having a problematic situation, while the maximum parallax on screen MPP provides the measure of the actual maximum horizontal positive disparity on screen given a specific acquisition and visualization setup. As described in [36]:

$$MPP \propto \frac{M \cdot f \cdot iax}{d_0} \tag{2}$$

where f is the focal length of the stereoscopic cameras, iax is the interaxial distance between left and right camera, d_0 is the distance between the stereoscopic camera and the convergence plane, and M is the screen magnification factor; i.e., the ratio of the display width to the width of the camera sensor.

If the MPP value of a given stereoscopic setup is lower than the native parallax NP of the display, then it is not possible to have an excessive positive parallax presented to the observer. If MPP is greater than NP, then it is possible that the positive parallax on screen of some objects will exceed the average human interocular distance, leading to a stereoscopic image painful to view. Particular care must be given to avoid these situations by changing the parameters of the stereoscopic acquisition or generation setup, or changing the content of the scene, by moving the objects at a less critical depth.

Window violation

Window violation is an issue related to the visualization of objects with negative parallax on screen (i.e., perceived in front of the screen). When these objects are “cut off” by the stereoscopic window (see Figure 1(a)), then there is a mismatch between the perception of depth elaborated using the parallax information (which tells that the object is in front of the screen) and the perception of depth given by the occlusion by the image frame (which tells that the object is behind the window border) [28,31]. Figure 1(b) shows the left and right views of a stereoscopic image presenting a window violation condition: a part of the object is visible only in one of the views, leading to the perceptual issue.

In stereoscopic movies production, the Dynamic Floating Window (DFW) technique [31] is usually used to remove window violations. This technique is based on the application of black masks at the borders of the frame to cover the visual information leading to the perceptual mismatch (see Figure 1(c)). In most of the cases, the black masks are applied in post-processing to the stereoscopic frame, even if recent works [37,38] have investigated the automatic detection of window violations, and the procedural application of the DFW technique. Moreover, some works have been presented on the application of this technique in real-time applications [39].

3 Stereoscopic visualization in a consumer-oriented HMD

In this paper, we have considered as case study the second pre-production version (Development Kit) of the Oculus Rift HMD. The Oculus Rift DK2 model has been provided by Oculus VR to developers in order to

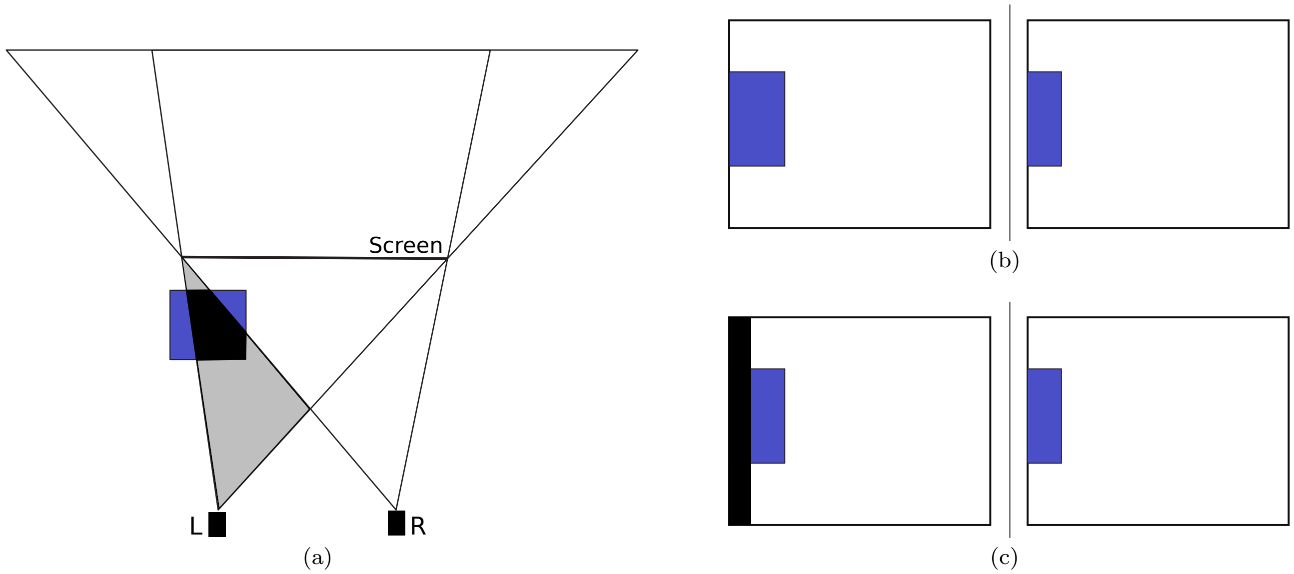


Fig. 1 Window violations may occur for objects perceived in front of the screen, which are partially outside the stereoscopic camera frustum. The scheme in Figure 1(a) shows an example of window violation: the cube is only partially visible, and the part of the cube inside the negative left frustum (in black) is visible only in the left view of the final stereoscopic image (Figure 1(b)), leading to a perceptual mismatch. In Figure 1(c), the Dynamic Floating Window technique has been applied: a black mask covers the part of the cube visible only in the left image.

allow them to design and test their immersive VR applications prior to the availability of the final consumer version.

The Oculus Rift DK2 is equipped with a 1920x1080 OLED display with a width of 125.77 mm and a height of 70.74 mm [40]. Pixel density is 15.26 pixel/mm. Stereoscopic visualization is achieved by presenting left and right view in a side-by-side format on the screen, and allowing each eye to see only the corresponding half of the screen. The declared distance between the eyes and the screen is 49.8 mm. To bring the image into focus and to achieve a wide FOV (106.19° vertically and 94.16° horizontally, as stated in Oculus SDK documentation [41]), two wide-angle lenses are placed in front of the observer's eyes (Figure 2). The lenses apply a pincushion effect on the images, that is compensated by applying a pre-warping (barrel distortion) of the image through a pixel shader [42]. The distance between the lenses can be adjusted between 55 and 75 mm, with 65 mm as default value [41].

To analyze the stereoscopic characteristics of the Oculus Rift DK2, we have modeled a simple test scene in Blender [43], composed by a cube (with side 1.5 m) and a room (with a length from the camera of 30 m). A checker texture (composed by 25x25 cm squares) has been assigned to the floor material. A preview of the scene can be seen in Figure 3. We have chosen Blender for this analys of the Oculus Rift DK2 because, among the different game engines and production softwares supported by Oculus VR, it is the only tool allowing to modify the parameters regarding the interocular distance and the camera FOV.

We have started our analysis by determining the native parallax of the Oculus Rift DK2 screen, and the maximum positive parallax on screen considering the overall production pipeline. Considering that each eye sees only one half of the screen, we determine the native parallax of the DK2 display applying Equation 1 as:

$$NP_{DK2} = \frac{65}{125.77 \cdot 0.5} = \frac{65}{62.885} \sim 1.0336$$

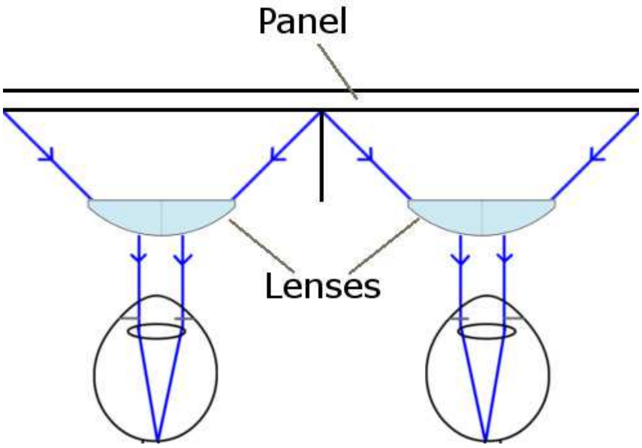


Fig. 2 Screen separation for left and right image visualization, and lenses placement inside the Oculus Rift DK2.

As a consequence, the screen of the Oculus Rift DK2 cannot display parallax values equal or greater than the average human interocular distance, and thus it is not subject to perceptual issues related to divergence situations on the background of the scene. To have a more precise measure of the actual maximum parallax achievable on the DK2 screen, we have applied Equation 2, considering the default dimension (32 mm) of the virtual sensor of the Blender camera to determine $M = 62.885/32 = 1.96$ and using $f = 14.88$, which is the focal length value corresponding to the 94.16° horizontal FOV of the Oculus Rift DK2:

$$MPP_{DK2} = \frac{1.96 \cdot 14.88 \cdot 65}{49.8} \sim 38.066mm$$

Therefore, the maximum parallax achievable on the Oculus Rift DK2 is only the 58% of the human interocular distance. This confirms the previous statement that the placement of objects in the virtual environment in the far background will never lead to painful values of parallax on screen. By considering the minimum (55 mm) and maximum (75 mm) values for the interaxial distance of the DK2 lenses, we obtain, respectively, $MPP_{DK2} = 32.2102$ mm and $MPP_{DK2} = 43.9228$ mm, which are in line with the previous result.

A peculiar characteristic of HMDs is that the placement of the “convergence plane” (i.e., where the parallax value is zero, and the objects are perceived on the screen) is not equal to the physical distance between the observer’s eyes and the screen, as it occurs in projection-based or monitor-based stereoscopic setups. To determine the virtual distance from the camera to the convergence plane in the Oculus Rift DK2, we have applied an empirical approach: in our test scene, we have gradually increased the distance in depth of the cube from the camera, and we have analyzed the changes in the disparity value given its position in the left and right rendered images. When the disparity value of the cube becomes zero, then the depth position of the cube gives the distance of the convergence plane in the Oculus Rift DK2 visualization setup. By using this approach, we have determined that, for the default interaxial distance of 65 mm, the convergence plane is at 2 m from the virtual camera. For the interaxial distances of 55 mm and 75 mm, the convergence plane distance becomes 1.60 m and 2.20 m, respectively. In Figure 3 we show the cube in the test scene, placed at the convergence distance, and we show the map of the disparities in the scene.

Therefore, there is a negative parallax area of about 2 virtual meters where it is theoretically possible to have window violations. Figure 4 shows an example where the cube has been placed between the camera and the convergence plane, only partially inside the view frustum of the camera. It is evident that the two views have different visual information, because part of the cube is not visible in the right image. However, these kind of window violations are less perceivable in a HMD than in other stereoscopic devices, because of the larger horizontal FOV, which moves the window violations in the peripheral vision, and because of the head tracking capabilities, which allows a continuous change of the visual information observed. However, for some immersive but not-interactive media, as the new kind of immersive movies currently produced for the new generation of consumer-oriented HMDs, this is an aspect to consider, if for some reasons the director aims at introducing some constraints in the free observation capabilities of these devices. In Section 4 we present the results of an experiment aimed at investigating the effect of window violations in large FOV HMDs.

3.1 Comparison with the stereoscopic setup of a standard 3D display

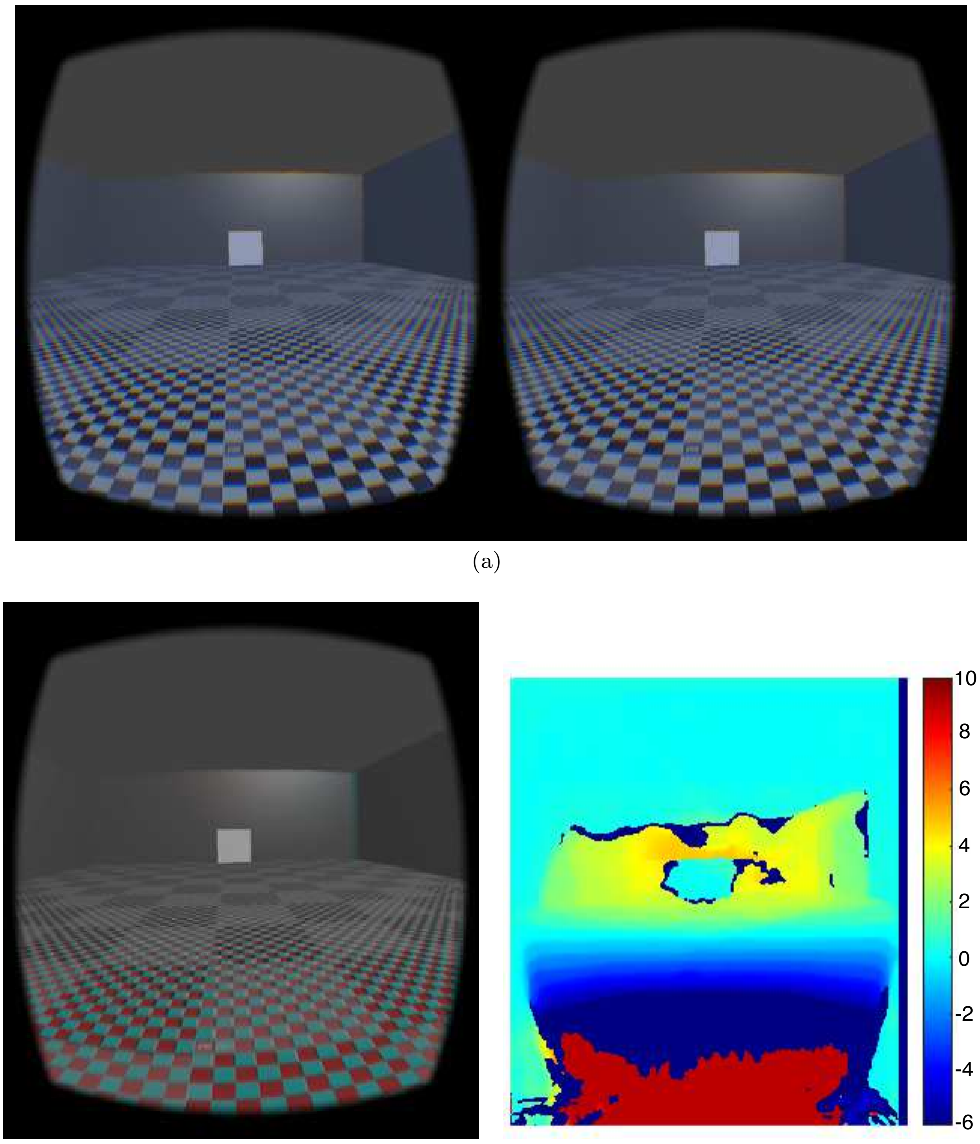
To better understand the peculiarities of a HMD stereoscopic visualization setup, we have decided to compare the stereoscopic characteristics of the Oculus Rift DK2 with those of a standard stereoscopic visualization based on a commercially-available 3D display. To this aim, we have considered a 27” LCD monitor (Asus VG278H 3D), with resolution 1920x1080 and physical dimensions of 600 mm x 340 mm, equipped with an active stereoscopy system.

Following the convention to calculate the optimal viewing distance for a Full HD panel as 3 times the panel height, we have set the observation distance of the viewer to the stereoscopic display at 1.02 m. Then, we have adapted our Blender test scene in order to make it match this different visualization setup, by setting the distance of the convergence plane at 1.02 m from the camera (i.e., setting a correspondence between the physical distance from the observers’ eyes to the screen and the virtual distance between the camera and the convergence plane in the Blender test scene), and the FOV value of the virtual camera at 32.78° (i.e., the view angle subtended by this visualization setup).

Applying Equation 1, the native parallax of the LCD display is:

$$NP_{LCD} = \frac{65}{600} \sim 0.1083$$

As for the Oculus Rift DK2, we have calculated the maximum parallax achievable on the LCD display. We have applied Equation 2 with $M = 600/32 = 18.75$ and $f = 54.4$:



(a)

(b)

(c)

Fig. 3 The test cube placed at the depth of the convergence plane (with interaxial distance 65 mm). Figure 3(a) shows the rendered test scene with barrel distortion applied before the visualization in the Oculus Rift. Figure 3(b) shows an anaglyph of the image: the parallax of the cube is zero, thus it is placed at the convergence plane depth. Figure 3(c) shows a disparity map of the scene to confirm the placement of the cube. (see the cyan area in the center of the map, please notice that the presence of the black area at the borders, due to the application of the pre-warping distortion, has introduced some artifacts in the bottom of the map.)

$$MPP_{LCD} = \frac{18.75 \cdot 54.4 \cdot 65}{1020} \sim 65mm$$

These values demonstrate how the stereoscopic disparity on the LCD display reaches the average human interaxial distance with a parallax on screen of approximately only 208 pixels (i.e., the 10.83% of the screen width). Thus, with this stereoscopic setup, the positioning of objects in the far background will easily lead to critical viewing situations, characterized by eye strain and fusion difficulties. As a consequence, a higher level of attention must be given during the production of stereoscopic content for a display- or projection-based stereoscopic visualization setup to avoid perceptual issues in the final results. HMD-based visualization, on the other hand, is not subject to these issues.

With respect to window violations, even if the negative parallax range is almost half of the range of the Oculus Rift DK2, the presence of this perceptual issue is more relevant, due to the absence of head tracking (the scene view is static, therefore it is not possible to avoid the retinal disparity through the natural process

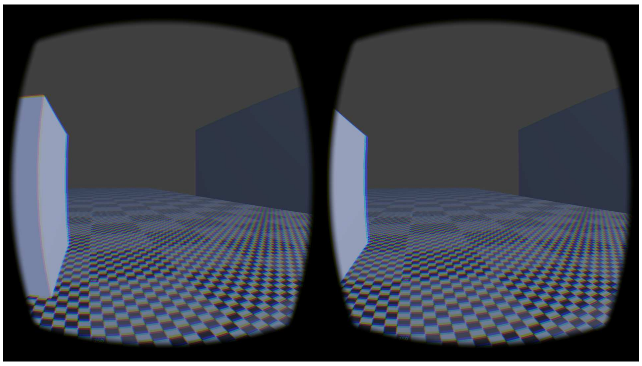


Fig. 4 An example of window violation in the Oculus Rift DK2.

of moving the head towards a new point of interest) and to the narrower FOV (the objects placed at the border of the screen are more evident because they fall in a more central retinal area). In Figure 5 we show a graphical comparison between the two different stereoscopic visualization setups.

4 Users feedback

To better investigate the differences in the two considered stereoscopic visualization setups, we have performed a test with a group of subjects, aimed at understanding their feedbacks during the presentation of stereoscopic stimuli characterized by the simultaneous presence of high values of negative and positive parallaxes on screen, and by the presence of window violations.

Subjects

20 undergraduate students have participated to the experiments. The subjects were 16 males and 4 females, between 20 and 24 years old (average age 21.11), all with normal vision or corrected to normal with eyeglasses or contact lenses. All subjects have tried at least once stereoscopy in a 3D movie theater, while 11 students (55% of the subjects) have already tried HMD visualization (with the Oculus Rift DK2 or other comparable devices). 4 subjects (20%) have reported problems during their previous experiences with stereoscopy in movie theaters (headache at the end of long movies), and other 4 subjects (20%) have reported vertigo and slight sickness after previous HMD visualization sessions.

Apparatus

We have considered the two stereoscopic visualization devices described and analyzed in the previous sections, connected to two different workstations of comparable computational power. For the experiments, we have considered a different version of our test scene, implemented using Unity game engine [44] for a better runtime support of the two setups. The scene is composed by two cubes: a red cube with side 1 m, placed initially at the depth of the convergence plane of the stereoscopic setup (i.e., at 2 meters from the virtual camera for the Oculus Rift DK2, and at 1.02 m for the stereoscopic display), and a blue cube with side 25 cm, placed initially at 50 m from the virtual camera (see Figure 6(a)).

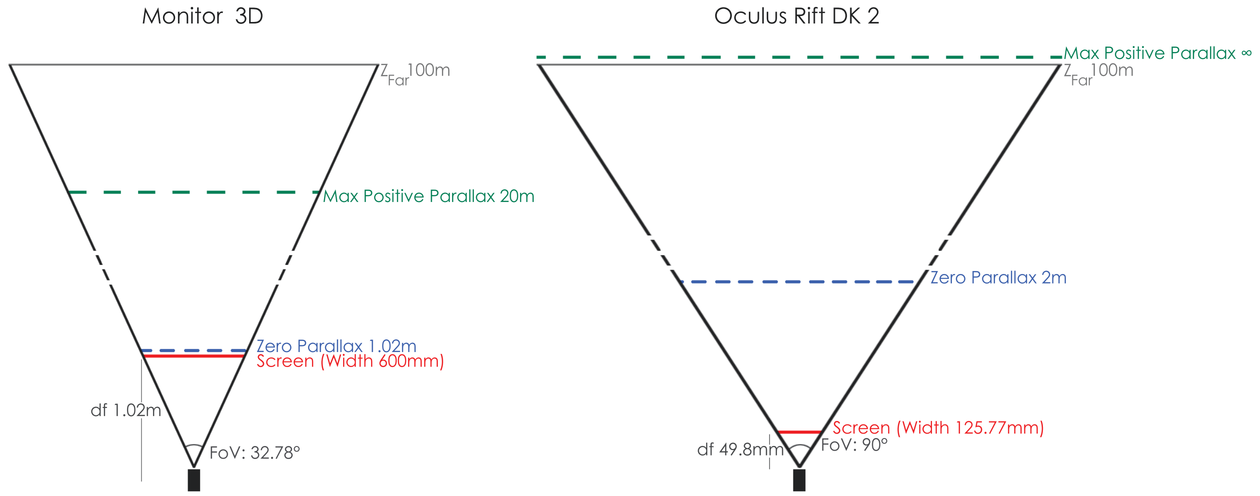


Fig. 5 Schemes of the different stereoscopic setups of the Oculus Rift DK2 and a standard 3D display.

Procedure

At the beginning of the experiments, each subject has been informed of the procedure and of the device characteristics. Some personal information has been collected for each subject, and a preliminary investigation of eventual previous experiences with stereoscopic or VR devices has been conducted. Each subject has been tested using the Oculus Rift DK2 in a first experimental session, and the stereoscopic LCD display in a second session, held after some minutes from the first. At the beginning of each session, the subject has been asked to sit comfortably on a chair, and she has been given a couple of minutes to get used with the HMD and the stereoscopic glasses. In the second session, the distance between the head of the subject and the stereoscopic display has been measured and eventually adjusted to be 1.02 m, as explained in Section 3.1. During the experiments, the room was darkened by switching off the lights to avoid interferences with the active stereoscopic setup used in the second session.

In both the sessions, the subject has been asked to report her feedback regarding the stereoscopic configuration of the scene. At the beginning of the session, the subject has been asked to get used at the initial spatial disposition of the cubes (see Figure 6(a)). Then, the red cube has been moved towards the bottom of the scene, reaching in 5 seconds the same depth of the blue cube (i.e., 50 m from the virtual camera). At the end of this first animation, the blue cube has been moved, at the same speed, from the initial position to a negative parallax position, equal to half the overall negative parallax range (i.e., the final distance of the blue cube from the virtual camera is 1 m in the Oculus Rift DK2 setup, and 0.51 m in the stereoscopic display). Figure 6(b) shows a red-cyan anaglyph preview of this configuration. During both movements, the subject has been asked to report if she was able to maintain the stereoscopic fusion from the beginning to the end of the animations, and if she was feeling eye strain or fatigue while looking at the cube in the background. The subject has been then asked to move the focus of her attention several times between the two cubes, and she has been asked again to report if she was feeling eye fatigue while alternating between the two different values of parallax on screen. In the final stage of the experiment, the blue cube has been moved on the left, reaching a window violation position (the amount of this horizontal translation has been adapted in the two setups in order to have the same amount of retinal disparity, see Figure 6(c) for a preview of the visual configuration). The subject has been asked to look at the red cube in the background, and then to move only the eyes to look at the blue cube, without moving her head, in order to avoid changes to the visual configuration of the scene (and, as a consequence, to the window violation configuration) due to the head tracking in the Oculus Rift DK2.

Results

After the experimental sessions, the subjects have been interviewed to determine their overall preference between the two stereoscopic visualization setups, and if they had some issues to report, related to some specific steps of the experiments. From the answers of the subjects, some interesting arguments can be identified. Regarding the visualization with the HMD, 6 subjects (30%) had reported they have been completely comfortable in all the experiment stages, with no issues to report. 9 subjects (45%) have reported moderate fatique in the stereoscopic fusion of the red cube when placed at the positive parallax position. The problem was not noticed in the same way by all these subjects during the same experiment stages: in fact, 3 subjects (15%) had some issues only when asked to change the focus from the blue cube to the red, and viceversa. After further investigations, it seems that the issue was not due to the amount of parallax on screen of the red cube (that from the analysis made in Section 3 is widely

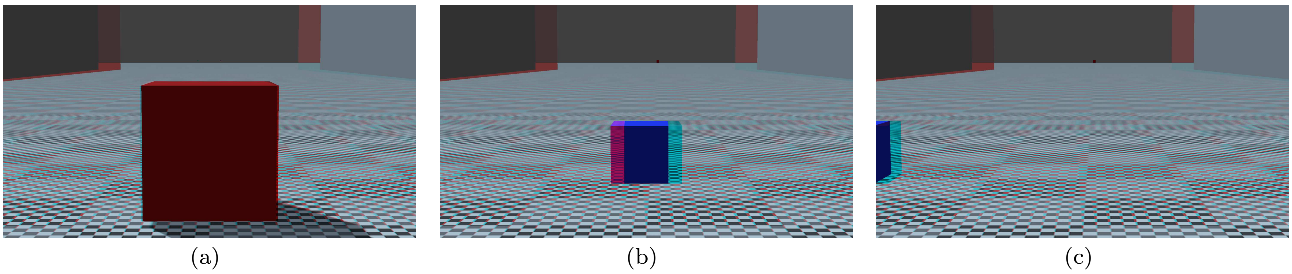

(a) (b) (c)

Fig. 6 Anaglyphic stereoscopic images of the three main configurations of the experiments: initial configuration (Figure 6(a)), presence of a relevant difference between negative and positive parallaxes (Figure 6(b)), window violation (Figure 6(c)). The anaglyphs are presented only as a preview of the stereoscopic content of the scene; during the experiments, the correct stereoscopic technology for each device has been used.

under the limit of the human interocular distance), but rather to the low resolution of the HMD display, which makes difficult a clear distinction of the cube edges and shape, and therefore a rapid and effective stereoscopic fusion. Interestingly, no issue has been reported for the blue cube in the initial configuration, even if the initial depth of the object was the same as the one of the red cube in the second stage. This is possibly due to the fact that the blue cube was smaller, and less noticeable in the background, and the subjects were not asked explicitely to look at it. Other subjects have reported minor issues: 3 subjects (15%) have reported slight fatique during a prolonged observation of the blue cube in negative parallax, while only 1 subject (5%) has reported issues with the blue cube in the window violation configuration, confirming our hypothesis that the retinal disparity is placed so laterally in the peripheral vision to not be fully perceived by the observer.

In the case of the stereoscopic visualization using the standard 3D display, a more uniform trend can be noticed. No issues have been reported by the subjects during the observation of the stimuli at positive and negative parallaxes, alone or alternated, as requested in the second stage of the experiment. However, 18 subjects (90%) have reported relevant difficulties in maintaining the stereoscopic fusion during the movements of the cubes from their initial and final positions. This is due to an excessive crosstalk level [45] in the 3D display: each eye was seeing a combination of the image intended for that eye, and some of the image intended for the other eye, and as a consequence some part of the image appeared “doubled” (which is the term used by most of the subjects to describe the issue). Moreover, almost all the students (19 observers, 95% of the subjects) had, as expected, relevant issues with the window violation configuration, reported as a continous flickering of the blue cube.

Interestingly, when asked for an overall preference between the two visualization setups, 7 subjects (35%) have indicated the Oculus Rift DK2, and 11 subjects (55%) the 3D display. 2 subjects (10%) have not indicated a preference. When asked to elaborate further their preferences, it was reported that, even if the stereoscopic visualization of the HMD was considered better than the 3D display, and particularly appreciated for the high immersivity, the head tracking functionality, and for the absence of crosstalk, the preferences of most part of the subjects had been influenced by the higher level of brightness of the 3D display, and by its higher resolution and sharpness (in particular for the objects in the background).

Discussion

It is reasonable to hypothesize that future HMDs models will overcome the limit we identified during the experiments with the adoption of more advanced displays characterized by a finer pixel rate and higher light emission. Anyway, it is of crucial importance that the overall design of dedicated media for the current generation of HMDs is accurately planned to overcome these drawbacks and to exploit instead all the strength points and potentialities of these kind of devices. Even if the stereoscopic features of HMDs allow a relevant freedom in the creation of immersive virtual environment, because many issues related to excessive parallax on screen and window violations are almost absent, an analyis of the most appropriate placement in depth of the objects of the scene will help to enhance the sense of immersivity and engagement, limiting the perception of the low sharpness due to the resolution of the screen.

From the results of our experiment, small objects placed far away from the camera are not easy to detect and to distinguish, as they appear blurry and grainy. Therefore, a possible guideline for a correct production of effective contents for HMDs could be to avoid small objects and fine details placed too far from the camera, but rather to lead the attention of the observer towards the scene features closer to the camera, exploiting the immersivity given by the device through the large FOV involved in the visualization and the head tracking capability. This can be achieved also by a clever use of lighting and shadowing, in order to blend the distant objects with a dark background. If large and open environments must be considered instead, another possible approach to decrease the blurriness for the far objects could be to increase their contrast with the background, in order to enhance as much as possible their visibility and the detection of their edges. This is not a trivial task, because different choices of the background and of the object colors can lead to different perceptual results [35,46].

5 Conclusion

With the recent diffusion of affordable VR-based devices, and the probable establishment of a complex and articulated interaction with different smart technologies and devices, such as the upcoming Internet of Things (IoT) technology wave, the correct production and development of dedicated content, designed to exploit the peculiarities of VR-enabling devices, is mandatory, in order to enable the creation of immersive applications for e-learning and diagnostic purposes.

In this paper, we have presented an analysis of the stereoscopic characteristics of a commercially-available Head Mounted Display, and we have determined that this kind of device does not present several issues typical of other stereoscopic visualization setups. Thus, we can argue that HMDs will enable a number of useful applications (such as social campaigns or educational contents) to improve their efficacy thanks to their deployment in VR settings. However, the limits in resolution and pixel density of the displays currently used must be considered in the production stage, because they can mislead the user in perceiving correctly small objects placed close to the maximum positive parallax, decreasing the sense of immersivity and the overall goal of the VR application. In this paper, we have identified and motivated under a technical perspective some possible guidelines to avoid these issues.

Even if the costant improvement of the portable display technology will overcome these limits in few years, the production of high quality and engaging VR contents is highly needed starting today, in order to affirm VR technology as a valid and effective tool to build useful applications that improve quality of life for their users.

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