Analysis of Stereoscopic Visualization in a Consumer-Oriented Head Mounted Display

Cinzia Vismara, Marco Granato, Laura Anna Ripamonti, Dario Maggiorini, and Davide Gadia(✉)

Department of Computer Science, University of Milan, Milan, Italy
`cinzia.vismara@studenti.unimi.it`, `marco.granato@unimi.it`,
{`ripamonti,dario,gadia`}`@di.unimi.it`

Abstract. The upcoming availability of advanced Head Mounted Displays (HMDs) dedicated to the consumer market has lead to a great interest in the design and development of dedicated media, like e.g. immersive video games and movies. As a consequence, Virtual Reality is becoming more accessible to a wider audience, with a large number of potential applications and integrations with already existing smart technologies and devices. HMDs 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 stage. In this paper, we analyze the stereoscopic setup of a HMD, in order to highlight its main visualization characteristics in relation with the known issues and requirements of a correct stereoscopic visualization, and to establish some preliminary guidelines for an optimal creation of stereoscopic contents.

Keywords: Head Mounted display · Oculus Rift · Stereoscopy · Stereoscopic media production · Stereo Window Violation

1 Introduction

Virtual Reality (VR) has been one of the most investigated research topics of the last years. Several applications of VR have been proposed in particular in industrial research (e.g., for the training of personnel involved in critical situations in dangerous environments [1]), or in medicine, due to the advanced visualization and simulation capabilities [2]. VR is largely used also in perceptual psychology, in order to replicate realistic situations in a controlled virtual setup [3]. Different approaches and technologies for VR visualization and interaction [4–6] have been proposed: the final choice of the most appropriate tools and solutions requires an accurate analysis of the goal of the simulation, of the number of users involved in the virtual environment, of the provided level of interaction, etc. [7,8].

Several works in the VR field are focused on the use of HMDs, because of their advanced immersivity and relatively affordable cost (if compared to large

O. Gaggi et al. (Eds.): GOODTECHS 2016, LNICST 195, pp. 274–283, 2017.
DOI: 10.1007/978-3-319-61949-1_29

projection-based VR systems). However, 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 the appropriateness of HMDs in presenting stereoscopic information [9]. In fact, the limited Field of View (FOV) of the previous generation of HMDs has often been considered one possible reason of the relevated underestimation of depth and distances in VR environments [10,11], even if other works [12,13] have suggested that this effect can be mitigated if the user can look around the environment without constraints.

However, a new generation of HMDs is becoming increasingly more available. These new devices are assembled using high quality electronic components already available for the construction of mobile or portable devices, and they are characterized by low latency, high resolution displays, and large FOV, with a price range relevantly lower than the previous HMD models. Moreover, some portable HMDs are even using smartphones as the main processing and visualization units. 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.

As a consequence, there is a growing interest in the production of dedicated media specifically designed to enhance the peculiar characteristics of HMDs, like e.g., immersive video games, and 360° stereoscopic movies. However, the production of stereoscopic media 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 [14,15].

In this paper, we will present an analysis of the stereoscopic setup of the Oculus Rift DK2 (Development Kit 2), in order to understand its visualization characteristics and stereoscopic performances, and to determine some preliminary 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 Oculus Rift DK2 with the visualization setup typical of a 3D monitor.

2 Stereoscopic Parameters

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, each sent only to the left or right eye of the viewer using specific hardware solutions. If the observer has an adequate stereoscopic ability [16], her visual system will process 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.

In the last few years, several solutions for the acquisition, elaboration and visualization of stereoscopic movies [14,15,17] and video games [18–20] have been proposed. In the presented analysis of the stereoscopic characteristics of a HMD, we will consider three crucial parameters: the *native parallax* of the display, the *maximum positive parallax* on screen, and the presence of *window violations* in the stereoscopic setup.

Native Screen Parallax. 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 [14]. It is calculated as:

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

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 [21].

Maximum Parallax on Screen. The production of a stereoscopic content requires an accurate comprehension of all the parameters and settings of both the acquisition/generation and visualization setups. The main goal is to avoid perceptual discomfort in the observer. One of the main source of discomfort is an excessive positive parallax on screen, which makes the process of fusion of the two views difficult, if not impossible, to the viewer. The native parallax NP gives the threshold, for a given 3D display, 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 [21]:

$$\mathrm{MPP} \propto \frac{\mathrm{M} \cdot \mathrm{f} \cdot \mathrm{iax}}{\mathrm{d}_0} \tag{2}$$

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 a problem 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, 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) [14,17].

In stereoscopic movie production, the Dynamic Floating Window (DFW) technique [17] is usually used to remove window violations. The 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. In most of the cases, the black masks are applied in post-processing to the stereoscopic frame, even if recent works [22,23] 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 [24].

3 Stereoscopic Visualization in the Oculus Rift DK2

The Oculus Rift DK2 is the second pre-production version (Development Kit) provided by Oculus VR to the developers community, in order to allow them to design, test and develop immersive VR contents prior to the availability of the final consumer version.

The DK2 model is equipped with a 1920 × 1080 OLED display with a width of 125.77 mm and a height of 70.74 mm [25]. 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 [26]), two wide-angle lenses are placed in front of the observer's eyes (Fig. 1). 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 [27].

The distance between the lenses can be adjusted between 55 and 75 mm, with 65 mm as default value [26].

To analyze the stereoscopic characteristics of the Oculus Rift DK2, we have modeled a simple test scene in Blender [28], composed by a cube (with size 1.5 m) and a room (with a length from the camera of 30 m). A checker texture (composed by 25 × 25 cm squares) has been assigned to the floor material. A preview of the scene can be seen in Fig. 2. We have chosen Blender as the production tool for our analysis because, despite the fact its internal Game Engine mode is not officially supported by Oculus VR as are other game engines, 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 Eq. 1 as:

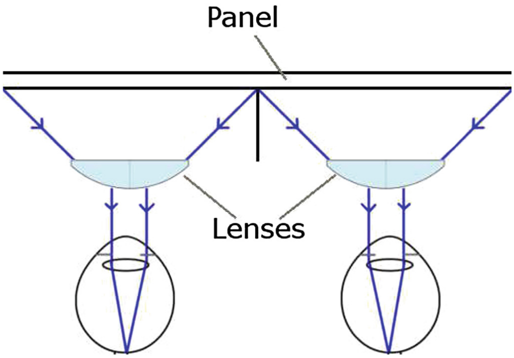


Fig. 1. Screen separation for left and right image visualization, and lenses placement inside the Oculus Rift DK2.

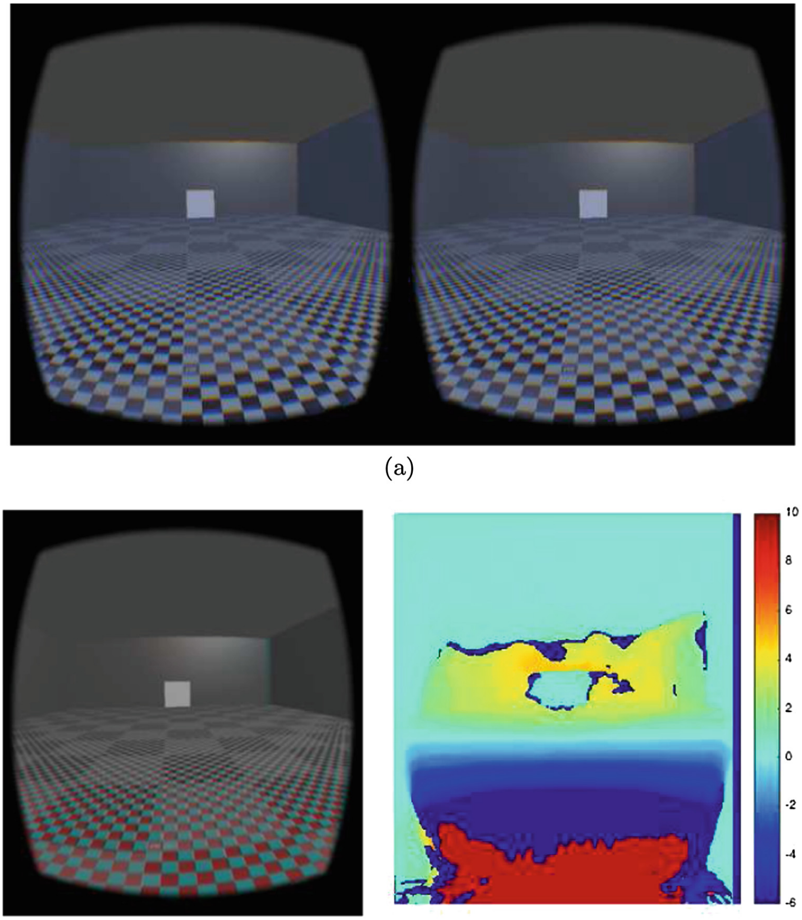
$$\mathrm{NP}_{DK2} = \frac{65}{125.77 \cdot 0.5} = \frac{65}{62.885} \sim 1.0336$$

As a consequence, the screen of the Oculus Rift DK2 can not display parallax values equal or greater than the average human interocular distance, and thus it is free from perceptual issues related to divergence situations on the background. To have a more precise measure of the actual maximum parallax achievable on the DK2 screen, we have applied Eq. 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:

$$\mathrm{MPP}_{DK2} = \frac{1.96 \cdot 14.88 \cdot 65}{49.8} \sim 38.066\,\mathrm{mm}$$

Therefore, the maximum parallax achievable on the Oculus Rift DK2 is only the 58% of the human interocular distance. As a consequence, the placement of objects in the virtual environment in the far background will never lead to perceptual issues or eye strain. In our preliminary tests, all the users have been able to correctly perceive objects placed at the bottom of our test scene. By considering the minimum (55 mm) and maximum (75 mm) values for the interaxial distance of the DK2 lenses, we obtain $MPP_{DK2} = 32.2102\,\mathrm{mm}$ and $MPP_{DK2} = 43.9228\,\mathrm{mm}$, respectively.

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 empyrical approach: we have gradually moved away from the camera the cube in our test scene, and we have analyzed the final disparity value given its position in the left and right views. When the


(a)

(b) (c)

Fig. 2. The test cube placed at the depth of the convergence plane (with interaxial distance 65 mm). Figure 2(a) shows the rendered test scene with barrel distortion applied before the visualization in the Oculus Rift. Figure 2(b) shows an anaglyph of the image: the parallax of the cube is zero, thus its depth is the depth of the convergence plane. Figure 2(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.)

disparity value of the cube becomes zero, then the depth position of the cube gives the distance of the convergence plane. 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 Fig. 2 we show the cube in the test scene, placed at the convergence distance, and we show the map of the disparities in the scene.

Finally, a preliminary analysis of the presence of window violations has been considered. Having determined the distance of the convergence plane, we know that there is a negative parallax range of about 2 virtual meters. In this area, it is theoretically possible to have window violations: Fig. 3 shows an example where our 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 at the periphery of sight, 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. Some perceptual experiments to investigate the effect of window violations in large FOV HMDs will be performed in the next months.

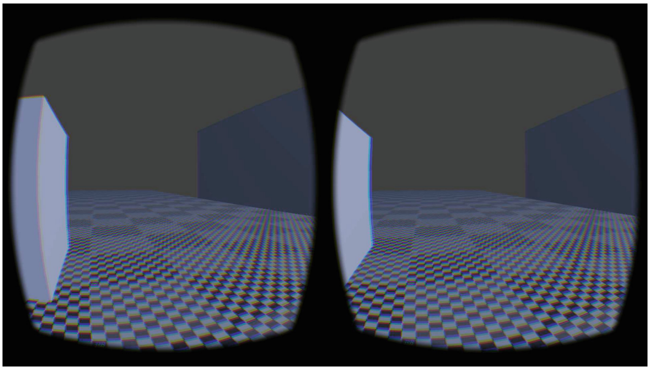


Fig. 3. An example of window violation in the Oculus Rift DK2.

4 Stereoscopic Setup of a Standard 3D Display

We have decided to compare the stereoscopic characteristics of the Oculus Rift DK2 with a standard setup used for stereoscopic visualization with a 3D monitor. We have considered a 27” LCD monitor (Asus VG278H 3D), with resolution 1920 × 1080 and physical dimensions of 600 mm × 340 mm, equipped with an active stereoscopy system. We have set the observation distance at 1.02 m, following the convention to calculate the optimal viewing distance for a Full HD panel as 3 times the panel height. Following this setup, we have adapted our virtual test scene in Blender by setting the distance of the convergence plane at 1.02 m from the camera (i.e., setting a correspondence between the physical distance between the eyes and the screen and the virtual distance between the camera and the convergence plane), and the FOV value at 32.78 (the view angle subtended by this visualization setup).

Applying Eq. 1, the native parallax of the LCD display is:

$$\mathrm{NP}_{LCD} = \frac{65}{600} \sim 0.1083$$

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

$$\mathrm{MPP}_{LCD} = \frac{18.75 \cdot 54.4 \cdot 65}{1020} \sim 65\,\mathrm{mm}$$

Thus, with a parallax on screen of approximately 208 pixels (only 10.83% of the screen width), the disparity is already equal to the average human interaxial distance. As a consequence, a higher level of attention must be given during the production of stereoscopic contents, to avoid perceptual issues in the final results. In fact, from the preliminary visualization tests, observers have reported relevant difficulties to correctly perceive stereoscopic images with screen parallaxes greater than 3 cm. These issues are due to the combination of the narrow FOV, display size and coarser pixel density of the LCD panel. Regarding 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, 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 Fig. 4 we show a graphical comparison between the two different stereoscopic visualization setups.

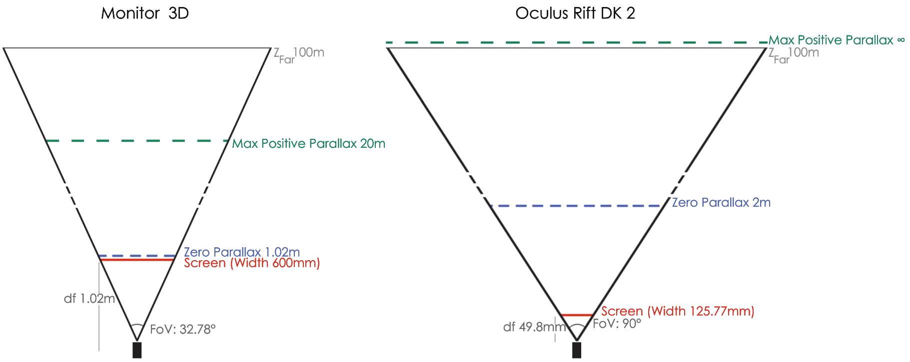


Fig. 4. Schemes of the different stereoscopic setups of the Oculus Rift DK2 and a standard 3D monitor.

5 Conclusion

In the next future, the consumer market for entertainment will see an increasing diffusion of Virtual Reality-based devices and stereoscopic content, due to the introduction of a new generation of advanced and affordable HMDs. With the probable establishment of a complex and articulated interaction between different smart technologies and devices, the production and development of dedicated content designed to exploit the peculiarities of these new visualization devices is mandatory. In this paper, we have presented an analysis of the stereoscopic characteristics of the Oculus Rift DK2, as a representative of this new generation of HMDs. We have determined that this kind of devices does not present issues related to possible excessive parallax values on screen, giving a relevant freedom to the developers to create immersive content without worrying about the final stereoscopic perception of objects placed in the background. Some additional accurate investigations are needed in order to evaluate if stereoscopic window violations are actually perceived in a relevant way, or if they are limited to some very specific configurations. Moreover, with the upcoming interest for online 3D interactive environments, it is also mandatory to extend our analysis to online collaborative applications, as already hinted in [29].

References

1. Ayala García, A., Galván Bobadilla, I., Arroyo Figueroa, G., Pérez Ramírez, M., Muñoz Román, J.: Virtual reality training system for maintenance and operation of high-voltage overhead power lines. Virtual Reality **20**(1), 27–40 (2016). Springer
2. Ruthenbeck, S.G., Reynolds, J.K.: Virtual reality for medical training: the state of the art. J. Simul. **9**(1), 16–26 (2015)
3. Wilson, C.J., Soranzo, A.: The use of virtual reality in psychology: a case study in visual perception. Comput. Math. Methods Med. (2015). Article ID 151702. https://www.hindawi.com/journals/cmmm/2015/151702/
4. Sherman, W., Craig, A.: Understanding Virtual Reality: Interface, Application, and Design. The Morgan Kaufmann Series in Computer Graphics (2002)
5. Craig, A., Sherman, W., Will, J.: Developing Virtual Reality Applications: Foundations of Effective Design. The Morgan Kaufmann Series in Computer Graphics (2009)
6. Bowman, D., Kruijff, E., LaViola, J., Poupyrev, I.: 3D User Interfaces: Theory and Practice. Addison-Wesley/Pearson Education, Boston (2004)
7. Marini, D., Folgieri, R., Gadia, D., Rizzi, A.: Virtual reality as a communication process. Virtual Reality **16**(3), 233–241 (2012). Springer
8. Barricelli, B.R., Gadia, D., Rizzi, A., Marini, D.: Semiotics of virtual reality as a communication process. Behav. Inf. Technol. **35**(11), 879–896 (2016). Taylor & Francis
9. Wann, J.P., Rushton, S., Mon-Williams, M.: Natural problems for stereoscopic depth perception in virtual environments. Vis. Res. **35**(19), 2731–2736 (1995)
10. Loomis, J.M., Knapp, J.M.: Visual perception of egocentric distance in real and virtual environments. In: Virtual and Adaptive Environments, pp. 21–46. CRC Prees (2003)

11. Kline, P.B., Witmer, B.G.: Distance perception in virtual environments: effects of field of view and surface texture at near distances. Hum. Factors Ergon. Soc. Annu. Meet. Proc. **40**, 1112–1116 (1996)
12. Knapp, J.M., Loomis, J.M.: Limited field of view of head-mounted displays is not the cause of distance underestimation in virtual environments. Presence: Teleoper. Virtual Environ. **13**(5), 572–577 (2004)
13. Willemsen, P., Gooch, A.A., Thompson, W.B., Creem-Regehr, S.H.: Effects of stereo viewing conditions on distance perception in virtual environments. Presence: Teleoper. Virtual Environ. **17**(1), 91–101 (2008)
14. Mendiburu, B.: 3D Movie Making: Stereoscopic Digital Cinema from Script to Screen. Focal Press, Waltham (2009)
15. Mendiburu, B., Pupulin, Y., Schklair, S.: 3D TV and 3D Cinema: Tools and Processes for Creative Stereoscopy. Taylor and Francis, Park Drive (2012)
16. Gadia, D., Garipoli, G., Bonanomi, C., Albani, L., Rizzi, A.: Assessing stereo blindness and stereo acuity on digital displays. Displays **35**(4), 206–212 (2014). Elsevier
17. Gardner, B.R.: Dynamic floating window: new creative tool for three-dimensional movies. J. Electron. Imaging **21**(1), 011009 (2012)
18. Schild, J.: Deep Gaming - The Creative and Technological Potential of Stereoscopic 3D Vision for Interactive Entertainment. CreateSpace Independent Publishing Platform (2014)
19. Bickerstaff, I.: Case study: the introduction of stereoscopic games on the Sony PlayStation 3. In: Stereoscopic Displays and Applications XXIII, Proceedings of SPIE, vol. 8288, p. 828815 (2012)
20. Weaver, J., Holliman, N.S.: Interlopers 3D: experiences designing a stereoscopic game. In: Stereoscopic Displays and Applications XXV, Proceedings of SPIE, vol. 9011, p. 90110F (2014)
21. Lipton, L.: Foundations of the Stereoscopic Cinema. Van Nostrand Reinhold, New York (1982)
22. Poulakos, S., Monroy, R., Aydin, T., Wang, O., Smolic, A., Gross, M.: A computational model for perception of stereoscopic window violations. In: Seventh International Workshop on Quality of Multimedia Experience (QoMEX), pp. 1–6 (2015)
23. Scalabrin, M., Ripamonti, L.A., Maggiorini, D., Gadia, D.: Stereoscopy-based procedural generation of virtual environments. In: Stereoscopic Displays and Applications XXVII, Proceedings of IS&T's 28th Symposium on Electronic Imaging: Science and Technology (2016)
24. Stanfield, B., Zerebecki, C., Hogue, A., Kapralos, B., Collins, K.: Impact of floating windows on the accuracy of depth perception in games. In: Stereoscopic Displays and Applications XXIV, Proceedings of SPIE, vol. 8648, p. 864814 (2013)
25. Oculus Rift DK2 Screen. http://www.theverge.com/2014/7/31/5956589/new-oculus-dev-kit-uses-front-of-galaxy-note-3-for-display. Accessed Mar 2016
26. Oculus Rift Developer Documentation. https://developer.oculus.com/documentation/intro-vr/latest/concepts/book-bp/. Accessed Mar 2016
27. Pohl, D., Johnson, G.S., Bolkart, T.: Improved pre-warping for wide angle, head mounted displays. In: Proceedings of the 19th ACM Symposium on Virtual Reality Software and Technology, pp. 259–262 (2013)
28. Blender homepage: http://blender.org. Accessed Mar 2016
29. Gerla, M., Maggiorini, D., Palazzi, C.E., Bujari, A.: A survey on interactive games over mobile networks. Wireless Commun. Mob. Comput. **13**(3), 212–229 (2013)