INTRODUCING VIRTUAL REALITY

A CLOSER LOOK ON THE RELATIONSHIP BETWEEN THE EMERGING FIELD OF

VIRTUAL REALITY AND VISUAL EFFECTS

AND IN WHICH WAYS THEY AFFECT EACH OTHER

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EIDESSTATTLICHE ERKLÄRUNG

„Hiermit versichere ich, Viktoria Rucker, an Eides Statt, dass ich die vorliegende Bachelorarbeit mit dem Titel: „INTRODUCING VIRTUAL REALITY - A closer look on the relationship between the emerging field of Virtual Reality and Visual Effects and in which ways they affect each other“ selbstständig und ohne fremde Hilfe verfasst und keine anderen als die angegebenen Hilfsmittel benutzt habe. Die Stellen der Arbeit, die dem Wortlaut oder dem Sinn nach anderen Werken entnommen wurden, sind in jedem Fall unter Angabe der Quelle kenntlich gemacht. Die Arbeit ist noch nicht veröffentlicht oder in anderer Form als Prüfungsleistung vorgelegt worden.

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Stuttgart, 31.03.2017 V. Rucker

Ort, Datum Unterschrift

ZIELGRUPPE

Dieses Bachelorarbeit ist für alle, die sich mit der Visual Effects- (VFX) oder Computer Generated Images (CGI) Branche befassen und sich für die Entwicklungen im Bereich von Virtual Reality (VR) interessieren. Es ist sowohl für Studenten als auch für Artists, Freelancer, ...; für jeden, der mehr über dieses neue Medium wissen und der ein besseres Verständnis von der Beziehung zwischen VR und VFX erlangen möchte. Da innerhalb der Thesis ein 360-Grad-VFX-Workflow genauer betrachtet wird, dient diese Arbeit auch als Grundlage für Leute, die VR gerne selbst ausprobieren möchten und einen ersten Eindruck über eines solchen Workflows gewinnen wollen. Der Leser sollte ein Grundwissen von VFX-, CG- und Game-Workflows haben, sowie eine erste Vorstellung davon, was VR ist. Darüber hinaus sind physikalische Gegebenheiten (wie zum Beispiel Licht, Optik, Klang) sowie die biologischen Aspekte der menschlichen Wahrnehmung Themen, mit denen man vertraut sein sollte.

KURZFASSUNG

Die folgende Bachelorarbeit soll einen Überblick über den sich entwickelnden Bereich von Virtual Reality geben und ein besseres Verständnis der Beziehung zwischen VR und Visual Effects schaffen.

Der erste Teil der Thesis befasst sich mit dem Thema Virtual Reality und wie sich dieses Medium bisher entwickelt hat. VR - Technologien (Head-Mounted Displays (HMDs), Kameras,…) und - Anwendungen werden ebenfalls erwähnt. Darüber hinaus ist die Arbeit in zwei Hauptteile unterteilt, die einerseits aus verschiedenen Ansätzen bestehen, um die Beziehung zwischen VR und VFX zu definieren und andererseits aus einem Versuch einen VR-VFX-Workflow näher zu betrachten. Bevor es um Probleme geht, die bei VR und VFX auftauchen, wird ein Fallbeispiel eines VR-Projekts beschrieben, das von einem VFX-Unternehmen produziert wurde. Außerdem werden VFX-Unternehmen, die nun auch VR-Inhalte produzieren, beleuchtet. Der letzte Teil befasst sich mit einen möglichen Ausblick für den VR-Bereich sowie für VFX-Unternehmen, die aktuell mit VR arbeiten, um dann mit einer Schlussfolgerung abzuschließen.

Anmerkung: Diese Arbeit beschäftigt sich nur mit VR, andere Formen wie Augmented Reality (AR) und Mixed Reality (MR) werden zwar erwähnt, aber nicht genauer betrachtet und erläutert.

TARGET GROUP

This paper targets individuals who are involved in Visual Effects (VFX) or the Computer Generated Images (CGI) industry and are interested in the emerging field of Virtual Reality (VR) which got more and more popular and accessible within the last two years. It is for students as well as for industry professionals such as artists,…; everyone who would like to know more about this new medium and who wants to gain a better understanding of the relationship between VR and VFX. As a 360 degree VFX workflow will be considered in detail, it is also a foundation for practitioners who want to gain a first impression about it. The reader should have a basic knowledge of VFX-, CG- and Game- workflows as well as have a first idea of what VR is. Moreover, physical principals (such as light, optics, sound), as well as the biological aspects of human perception are topics which one should be familiar with.

ABSTRACT

The following thesis should give an overview about the emerging field of Virtual Reality and create better understanding of the relationship between VR and Visual Effects.

In the first part, the aim is to get an introduction of what Virtual Reality is and how it developed so far. VR basics, technology (head-mounted displays (HMDs), cameras…) and applications will also be mentioned. Furthermore, the paper is divided in two main parts which consist on the one hand of different approaches to define the relationship between VR and VFX and on the other of a gradual rapprochement to a VR-VFX workflow. Before evincing issues concerning VR and visual effects, there will be a case study of a VR project produced by a VFX company and an analysis of VFX companies doing VR at the moment. The last part covers a possible outlook for the field of VR as well as for VFX companies being working with VR right now. As last step a conclusion will be made.

Annotation: This thesis is primary dealing with VR, other forms like Augmented Reality (AR) and Mixed Reality (MR) are mentioned, but not considered profound and explained in detail.

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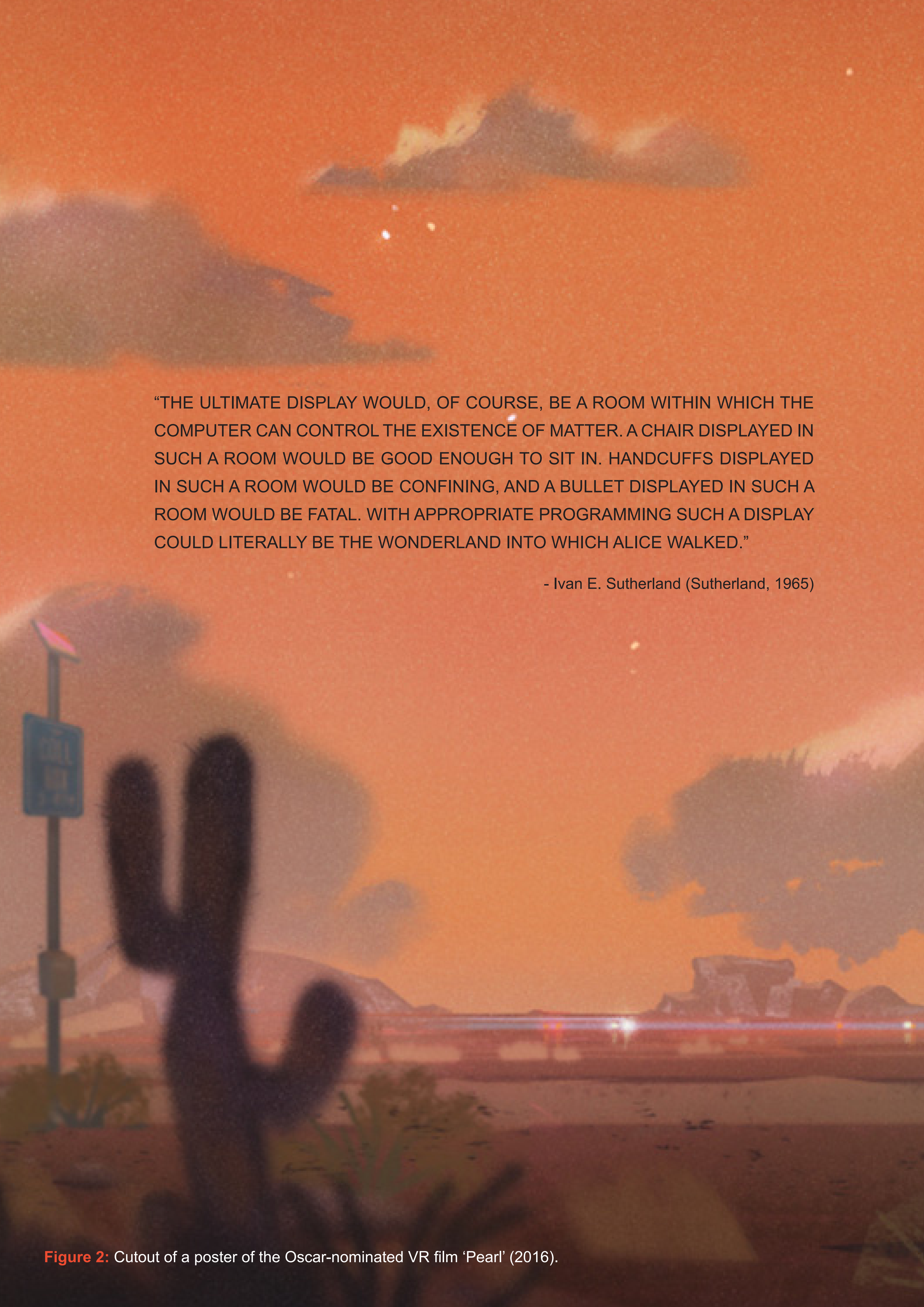
Figure 1: VR, Variety cover, March 22nd, 2016.

CONTENT

1

INTRODUCTION



“THE ULTIMATE DISPLAY WOULD, OF COURSE, BE A ROOM WITHIN WHICH THE COMPUTER CAN CONTROL THE EXISTENCE OF MATTER. A CHAIR DISPLAYED IN SUCH A ROOM WOULD BE GOOD ENOUGH TO SIT IN. HANDCUFFS DISPLAYED IN SUCH A ROOM WOULD BE CONFINING, AND A BULLET DISPLAYED IN SUCH A ROOM WOULD BE FATAL. WITH APPROPRIATE PROGRAMMING SUCH A DISPLAY COULD LITERALLY BE THE WONDERLAND INTO WHICH ALICE WALKED.”

- Ivan E. Sutherland (Sutherland, 1965)

Figure 2: Cutout of a poster of the Oscar-nominated VR film ‘Pearl’ (2016).

These are the last sentences from Ivan E. Sutherland's essay 'The Ultimate Display' which originated in the context of his research of immersive technologies in 1965 (cf. Sutherland, 1965). He is one of the godfathers and pioneers in the field of computer graphics and the creator of 'Sketchpad', a revolutionary computer program for which he won the Turing Award[1] in 1988. Modern object oriented programming as well as the graphical user interface (GUI) derived from its program. In his paper 'The Ultimate Display' he presents his vision of a future Virtual Reality and its potential (cf. Sutherland, 1965). He describes a futuristic display "which allows users to immerse themselves into computer-generated environments via novel types of multimodal input and output devices" (Steinicke, 2016, p.19). In this world the user is completely immersed in a computer-mediated environment and not able to distinguish between the virtual surrounding and the real world. It is a play with perception and the screen of the computer functions more like a window into a virtual world which looks, moves, interacts, sounds and feels real instead of just displaying information (cf. Bye, 2016).

Other prominent examples, which address this phenomenon, can be found in literature, film and science fiction arts. 'Plato's Allegory of the Cave'[2] is an example referring to the old century, but there are also several modern science fiction movies like 'World on a Wire' (1973), 'The Lawnmower Man' (1992), 'The Matrix' (1999), 'Surrogates' (2009) or 'Avatar' (2009) dealing with "this perceptual ambiguity" (Steinicke, 2016, p.20). "These fictional works often show different forms of VR-enabled world-building or cosmos construction that serve as a means of making sense of our own world" (ibid. p.20).

Sutherland's vision of 'The Ultimate Display', as well as the examples mentioned above, show a really futuristic "notion of a VR, which is indistinguishable from the real world" (Steinicke, 2016, p.19 f). Nowadays, we are still apart from full immersion within this technology, but the VR development grew in the last two years and technology will improve. Thus to the recession of the VR technology in the last 20 years, 2016 promised to be a huge year for the comeback of VR and was therefore often traded as 'The year of VR' (cf. Hamilton, 2016).

1 A prize given annually by the Association for Computing Machinery (ACM) to persons who have made a special contribution to the development of computer science.

2 The most famous parable of the ancient philosophy of the Greek Philosopher Plato (428/427–348/347 v. Chr.).

1.1 MOTIVATION

As already mentioned in the introduction, 2016 was traded as “The year of VR” (Hamilton, 2016) or better said “Year Zero in the VR timeline” (Lee, N. 2016) for the new growing medium.

To put in the words of Robert Scoble, founder of the website UploadVR and one of the best-known online tech journalists, and Shel Israel, author of several books as well as keynote speaker at business and tech conferences, “We are now at the dawn of the Fourth Transformation” (Scoble, & Israel, 2017, p.xx). This statement is an interesting approach to VR and is a major subject in their new book ‘The Fourth Transformation’.

According to them, we already passed through three transformations in the way we interact with computers. The first one refers to the MS-DOS which IBM licensed from Microsoft in 1981 (cf. Scoble, & Israel, 2017, p. xix). Through using text characters to interact with computers, it was easier for people to get access to computers and the possibility to interact in more personal ways. The next transformation came along with the Graphical User Interface (GUI) and with introducing the Macintosh (Apple) and Windows (Microsoft). The GUI was a necessary part to a user-friendly interface and improved personal computing as well as it worked as stepping stone to the worldwide web (cf. Scoble, & Israel, 2017, p.xx). In 2007 the third transformation came with the iPhone, followed by other smartphones such as, for instance, Android or Windows phones. Personal computing was now possible from everywhere and the primary interface was touch. With this third transformation the center of our digital lives has moved from our desktop to the devices (tablet, phone) we carry around (cf. ibid. p.xx). The fourth transformation should change these habits again. The devices will change from what we carry around to what we wear and from interface between technology and people to experience (cf. ibid. p.xx).

They mention in their book that after “typing, clicking, touching”, “interacting” will be defining the new era of transformation (cf. ibid. p.57). The book which got released in the beginning of 2017 shows how present the VR topic is right now and how it could influence our lives in future.

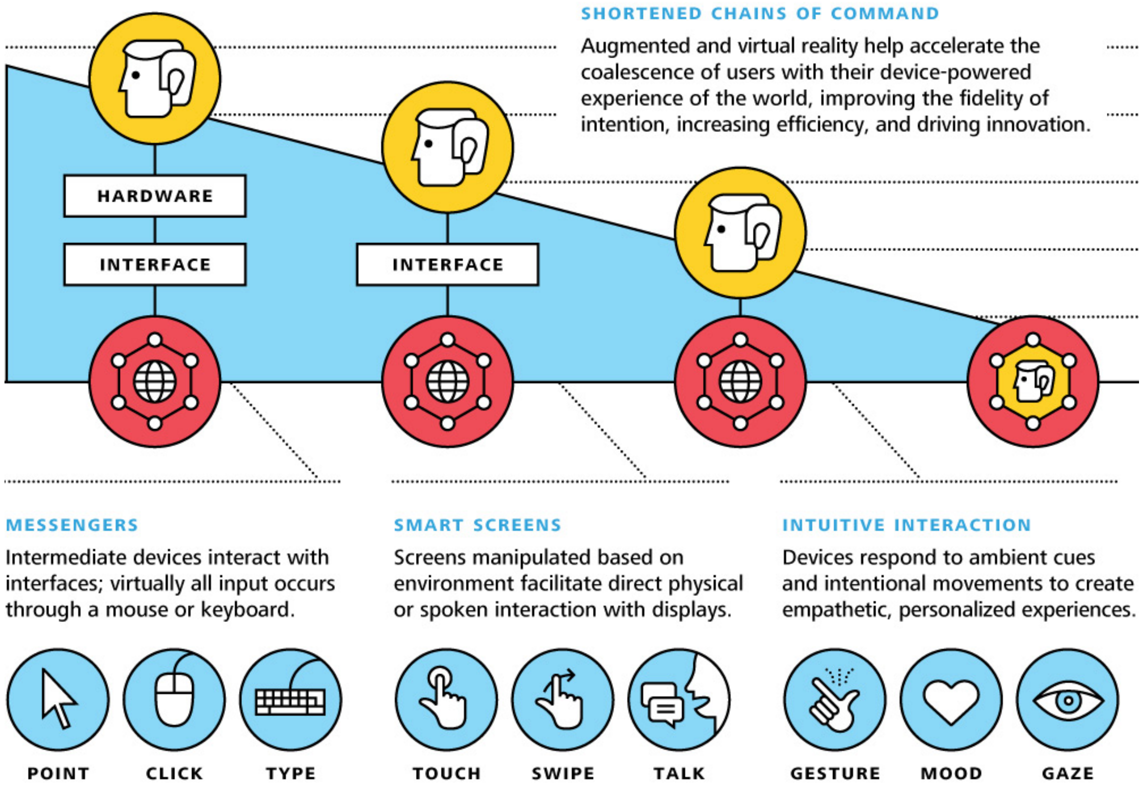


Figure 3: The evolution of interaction, Deloitte University Press.

Regarding the VR equipment it is noticeable that this was extremely expensive in the past and only for research and development purposes, thus not accessible for masses. Through the releases of big, influential tech companies such as Oculus (Facebook), Google, HTC or Samsung last year (2016) it got easier for people to get access to VR. The availability of devices and the permanent development of game engines, software, head-mounted-displays and tools in the last year was the first step of Virtual Reality becoming a potential mass medium in the future. More and more people have now the possibility to experience VR and are even able to create VR content on their own. Moreover, VR gains more public attention through trusted brands creating VR content, e.g. Ikea, Volvo or the hotel group Marriott which provided 360 degree experiences for their customers.

YouTube 360° reached more than two million people subscribing to their channel (cf. “YouTube 360° - Virtual Reality”, n.d.) and also Vimeo has now the possibility to stream 360 degree content which is also a sign for the increasing attentiveness for this new medium.

A recent research on the Virtual Reality landscape in Europe of The Venture Reality Fund and LucidWeb shows that there are nearly 300 companies in the VR ecosystem across Europe so far (cf. “EU VR Industry Landscape”, 2017). “The VR industry is booming and not just in the U.S. or Asia” (Takahashi, 2017) indicates Leen Segers, cofounder and CEO at LucidWeb, concerning this subject.

In addition, VR was present on all major creative as well as technical exhibitions last year, for example on FMX, SIGGRAPH, IFA or CES, to just name some. Besides that, all over the world panels and conferences for VR were popping up because people want to discuss and learn more about this evolving area (cf. Coulombe, 2016). To put it in the words of Solomon Rogers, CEO and Founder of Rewind, “Virtual reality has never before enjoyed such mainstream acceptance and awareness” (Rogers, 2016).

Furthermore, it is noticeable that also several VFX companies are concerned with the creation of VR content. Besides that, there was another milestone for VR in the beginning of 2017. The first Academy Award[3] nomination for VR content was announced for the 360 degree animated short film ‘Pearl’, which was directed by Patrick Osborne and produced by Google Spotlight Stories and Evil Eye Pictures. This nomination in the category “Best animated short” brings also attention to VR (cf. Feltham, 2017).

Like covered in the section above VR showcases as a current and exciting topic, which is present in all different areas of life and all kinds of industry branches. In this thesis, there will be a closer look on the Visual Effects sector. It is striking that a lot of well-known VFX companies got engaged in VR technology throughout the last two years. Andrew Cochrane, interactive and new media director at Mirada’s VFX Studios, mentioned on a VES production summit 2015 in Hollywood that the evolving field of VR “could be the saving grace” (Giardina, 2015) for Hollywood’s struggling VFX community. After the Visual Effects crisis in 2013[4] it really could be “the saving grace” (ibid.) for a Visual Effects house to have a VR department as second income besides the VFX business.

This topic and different approaches how VR is connected to VFX will be the main part of this thesis as well as a gradual rapprochement to a VR workflow. The whole structure will be particularly covered in the next step.

3 Best known as the Oscars - Movie Award annually given by the Academy of Motion Pictures Arts and Sciences (AMPAS).

4 With ‘Life of Pi‘s‘ Oscar win in 2013 and the bankruptcy of the VFX company that made the Visual Effects for it (Rhythm and Hues), a worldwide dialogue in the VFX industry came up, adressing issues and troubles in the VFX sector.

1.2 STRUCTURE

The general outcome of this thesis should be to get an overview of Virtual Reality, give insights in the different connections between VR and VFX and highlight these through examples.

In the first part of the thesis the aim will be to show the recent situation of Virtual Reality: What is the current state of VR right now? This includes a definition, a short retrospective of VR history, as well as an overview of existing technology (HMDs, cameras …) and possible applications in our all-day lives.

The goal of the main part of this thesis is to examine the current rise of Virtual Reality and what the resulting consequences for the Visual Effects industry are. There are several ways to approach the relation of VFX and VR. Not only VFX techniques can be applied to the VR workflow but VR could also be used for VFX productions as a tool, for example for Virtual Production or previsualization. Besides that, effects can also be integrated in VR projects under certain circumstances. In all cases, there are still numerous challenges to overcome and issues to solve. These will be thoroughly covered and in the following, there will be an approach to a VR workflow that shows similarities and differences to a normal VFX workflow.

Furthermore, a case study of a VR project by a well-known VFX-company will be introduced and it will be pointed out how VFX relates to VR. Moreover, several employees of VR departments of several VFX companies were surveyed to examine why companies with their origin and background on VFX and Animation get involved into VR business. The results will be integrated throughout the thesis. At the end, problems and challenges of VR are described. There are several ones to face, just like post-production difficulties, no suitable business models or ways to monetize VR content and no unified standardization, neither in naming conventions nor in workflows.

Following this, some future predictions for the following years will be dealt with and an outlook of how the future of VR could look like and what role Visual Effects could play in that, will be given. In a final step there will be some concluding words concerning the VR branch and its relationship to the VFX industry.

2

VR OVERVIEW

"IT'S SOMETHING BRAND NEW,
LIKE TELEVISION WAS TO THEATER."

- Robert Stromberg (Lalwani, 2016)

Figure 4: Screenshot from the movie 'The Matrix' (1999), 'Red or Blue Pill?'.

Cave painting
Written language
Sculpting (e.g., totem poles)
Musical notation
Books (hand written)
Books (printing press)
Newspapers (periodical information)
Telegraph
Photography
Stereoscope (Wheatstone)
Stereo photography
Recorded Audio
Animated images
Motion pictures (mass visual presentation)
Telephone
Radio
Television (mass visual presentation)
Digital computer (ENIAC)
Flight Simulation
Computer graphics (sketchpad)
First HMD (Sutherland)
Video games
Picture phone
Video teleconferencing
Internet (telnet, ftp, socket, etc.)
Color frame buffer for computers
Networked computer discussion forums
Stereo computer graphics
Immersive interactive computer display
The CAVE (a theater-like VR venue)
The World Wide Web

Figure 5: Progression of new media and achievments of humankind over time. Adapted fr. Sherman, & Craig, 2003, p. 6.

We are staring at rectangles for a long time: from paintings to TV-, computer-, smartphone- or cinema screens. That is why people need to adapt to the new way of experiencing content provided by VR technology. They need to get used to this new medium, as well as accept it. Robert Stromberg, CEO of VRC, refers in his quote “It's something brand new, like television was to theater” (Lalwani, 2016) to a time where TV was an unknown medium and then led to a change in consumer behavior. The *figure 5* shows the progression of new media and achievement of humankind over time. There have always been major inventions of new mediums, such as for example TV, computer, mobile phones or smartphones, which had an huge effect on society and the way we are consuming content. Every means of information dissemination needs to pass through the stages of innovation, acceptance and naturalization in society (cf. Stăiculescu, & Nădrag, n.d.). And VR is still in its development and early acceptance phase.

In this chapter the medium VR will be in focus. At what point is VR standing right now? What does it mean? Which components come along with it? A basic overall view will be given, including a short retrospective of VR history and why VR is gaining more interest right now, as well as an overview of existing technology (HMDs, cameras …) and possible applications in our all-day lives.

The topic Virtual Reality is so comprehensive, that covering everything of it will be beyond the scope of this thesis. As there is still the main focus on the VR workflow as well as on the connection between VR and VFX, this chapter serves only as VR overview.

2.1 WHAT IS VR?

There are different ways to approach this question. But before trying to get close to an extensive definition of VR there must be mentioned that there are also two other forms which differentiate from VR. For one thing, this is Augmented Reality (AR) and secondly Mixed Reality (MR). Whereas VR puts you in an entirely new place and lets you forget the surroundings of the real world, AR shows the normal world especially extended with extra information in form of digital content. So to say, it is an extension of the real world. Regarding MR you can say it is a hybrid form of VR and AR. There is also an integration of digital objects in the real world like in AR but these objects seem to look like they belong to that world, they are now placed in relating to VR. It is important to know the difference between these forms but from now on AR and MR won't be in main focus throughout this thesis.

Figure 6: VR, AR and MR comparison.

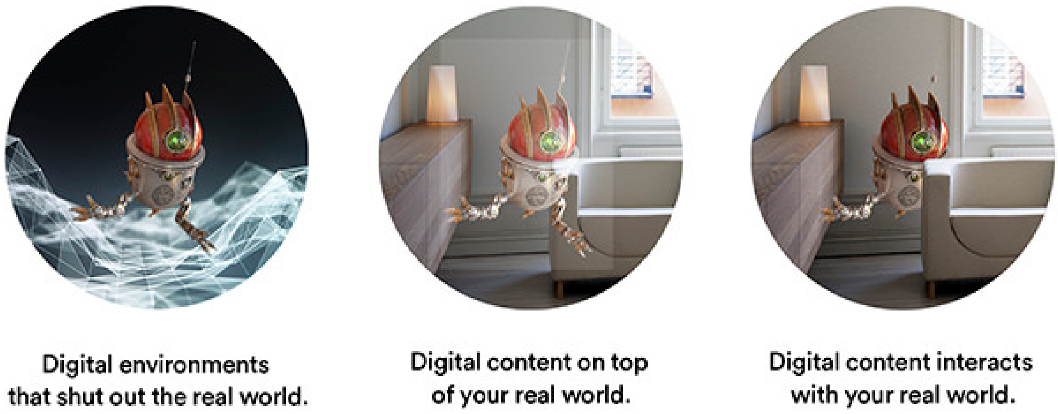


Figure 7: VR, AR and MR examples. Different digital realities represented by Magic Leap.

2.1.1 DEFINITION

The term 'Virtual Reality' became popular through the American computer scientist and VR pioneer Jaron Lanier in the late 1980s. There were also a lot of other people dealing with VR but he was the first one to give it a name (cf. Steinicke, 2016, p.29).

Since then, the definition of VR is still in flux and as already mentioned there are different approaches and various kinds of definitions, interpretations and opinions among miscellaneous people throughout the years. There are different people with other point of views and purposes as well as distinct basic knowledge of the field of VR. Thus it is comprehensible that a researcher has another notion of what VR means than for instance an average consumer or someone working in a marketing department. As long as there is no standardization for VR, there will not be a unite definition.

In Media, VR has often been used in a misleading way and got equalized with other terms such as 'cyber world' or 'virtual world' which relates more to 'Second Life'[5] or other virtual online games like 'World of Warcraft'[6] than to a Virtual Reality experience (cf. Steinicke, 2016, p. viii).

As already mentioned, a constant debate about a common definition of the term 'VR' keeps running. But if one considers the linguistic perspective of the term 'Virtual Reality', it consists of two composite parts: the adjective 'virtual' and the noun 'reality'. The term 'Virtual Reality' seems to be an oxymoron due to its discernible contradiction between the two words (cf. Steinicke, 2016, p. viii). According to the Oxford dictionary 'virtual' is described as "not physically existing as such but made by software to appear to do so" ("virtual - definition of virtual in English | Oxford Dictionaries", n.d.) and 'reality' can be seen as "the state of things as they actually exist, as opposed to an idealistic or notional idea of them" ("reality - definition of reality in English | Oxford Dictionaries", n.d.). Whereas 'reality' is complicated to define and could lead to complex philosophical discussions you can simplify this by saying it is a place that exists and you are able to experience (cf. Sherman, & Craig, 2003, p.6).

One definition which got published over 20 years ago in the International Journal of Virtual Reality describes Virtual Reality as "a computer system used to create an artificial world in which the user has the impression of being in that world and with the ability to navigate through the world and manipulate objects in the world" ("Real time simulation: VR for Urban Planners", 2010).

Another approach is the explanation from the researcher and professor of the University of Illinois Steven M. LaValle who just wrote the following definition in his paper 'Virtual Reality': "Inducing targeted behavior in an organism by using artificial sensory stimulation, while the organism has little or no awareness of the interference" (LaValle, 2017, p.1 ff.). His definition of Virtual Reality consists of four key components. The first one is the targeted behavior, meaning that the user is experiencing something, which was designed by a creator. As second component he mentions is the organism itself. That could be every person or even other life forms, such as animals. The third element deals with artificial sensory stimulation which means that through technical efforts it is possible to create artificial stimulations. By that, the brain can be tricked and these stimulations are interpreted as ordinary inputs. The last component is awareness. This means that the user is unaware of being situated in a virtual world and thus accepting this world as being natural (cf. LaValle, 2017, p. 1 ff.).

5 A virtual world in 3D. Users are able to connect, socialize and create their own virtual world.
6 Online game devloped by Blizzard Entertainment.

These examples were picked among lots of other definitions to show some different perspectives. For the scope of this thesis the following definition will be pursued throughout the thesis. The essential point all definitions have in common is that VR is a virtual environment which feels in best case real and hence is indistinguishable of the real world. In fact you feel physically and mentally engaged in the virtual environment in which you are also able to interact.

To achieve VR you need the ability to produce a virtual world that replicates either a real or imagined environment. That can be attained by video capture or due to generating a computer-generated environment. Besides that, a device is needed to be able to get immersed in a virtual environment. This could be a room or a headset, also called head-mounted display (HMD). Such a device allows the user to interact and experience a virtual world in ways that feel like if he or she is really there. The state of being fully immersed and feeling completely transferred in another world is called presence and will be covered in the next section.

2.1.2 IMMERSION | PRESENCE

Two components that always come along with VR are immersion and presence. Jason Jerald offers a definition for immersion in the book 'The VR book: Human-Centered Design for Virtual Reality': "Immersion is the objective technology that has the potential to engage users in the experience" (Jerald, 2016, p.46). So to say, the brain is tricked by technology and the user perceives the virtual world as real environment. Immersion cannot control the mind but lead it (cf. ibid. p.46). According to the computer scientist Jonathan Steuer, two main elements of immersion can be deduced. As one of these elements, he defines the depth of information which applies to the amount and quality of data a VR system provides. This concerns the display's resolution, complexity of graphics in the environment or audio output and so on. The second element is the breadth of information which Steuer defines as the "number of sensory dimensions simultaneously presented" (Steuer, 1993, p.11). He relates to the amount and which senses got stimulated. Full immersion could be achieved if not only seeing and hearing but also other senses, like touch, taste and smell appear and feel real in a virtual environment. In this case brain and senses work together to give the user feedback of immediate surroundings. But the slightest distraction could lead to the event that the user falls out of experience because our brain and senses will recognize that immediately (cf. Eisenberg, n.d.). Overall, you can say that immersion is the "perception of being present in a non-physical environment" (ibid.). In their book 'Understanding Virtual Reality', Sherman and Craig point out that there is a difference between physical and mental immersion. Whereas physical immersion is a defining characteristic for VR describing the body entering a VR system which gives stimulus to participants' senses via technology, mental immersion refers to 'sense of presence' (cf. Sherman, & Craig, 2003, p. 9). Being mentally immersed can be compared to the "internal psychological and physiological state of the user" (Jerald, 2016, p.46). The way a user experiences immersion is known as presence. Presence is on the one hand dependent on immersion, on the other hand on the user. The technology must be capable of providing the immersion but it still does not mean that the user is automatically present and can imagine being in another world. (cf. Jerald, 2016, p.46). "Presence is however, limited by immersion; the greater immersion a system/application provides then the greater potential for a user to feel present in that virtual world" (Jerald, 2016, p.46).

In a quote the VR pioneer Jaron Lanier states "The mind has a strong desire to believe that the world it perceives is real" (Zachman, 2010) which is a fundamental fact that allows VR to work. This quote also refers to the expression 'willing suspension of disbelief' which got shaped by the philosopher Samuel T. Coleridge. People are eager to empathize with a virtual world even if it is just a really abstract one, like for instance a drawn Disney movie where animals can talk (Dörner, et al., 2013, p. 8). If the world is believable, the user can feel present in it and be transported in another world. That means that the world does not have to be photorealistic for people feeling present in it if things such as interaction or spatial audio are provided (cf. Strickland, 2007).

A special form of presence, which should be mentioned, is 'telepresence'. It is a combination of immersion and interactivity and provides the ability to navigate and modify a remote environment. In the book 'Understanding Virtual Reality' telepresence is seen as "the ability to directly interact (often via computer mediation) with a physically real, remote environment from the first-person point of view" (Sherman, & Craig, 2003, p.20). Telepresence can be for example used for remote operations such as manipulating probes in the deep see or working with toxic chemicals (cf. ibid.). Like with the definition of Virtual Reality, a lot of people have different opinions and ways to approach these terms.

2.2 HISTORY

Some people say that the concept of VR goes back to cave paintings and murals and that VR had its first primitive attempts in art. For example, impressionist and panoramic paintings also support the idea of making people feel present in another location through intending to fill the viewer's entire field of vision and for instance to put him in an historical event or scene ("History Of Virtual Reality – VRS Society", n.d.). Also the invention of the rudimentary Victorian stereoscopes can be seen as a first approach to VR. Low budget headsets like for instance the Google Cardboard use the same design principles of these.

VR has a long research history and its actual origin in military. In 1929 Edward Link develops the first commercial flight simulator for military purposes. It was an easier and safer way to train pilots and improve their skills. But VR as we know it nowadays was created by a handful of people in the 1960s. In 1962 the cinematographer Morton Heilig presented the single user console, the Sensorama (cf. *figure 8*), an experience that covers all senses. It "included a stereoscopic display, fans, odor emitters, stereo speakers and a moving chair" (Strickland, 2007). But it was not possible to commercialize his visionary prototype for a cinema of the future. In a later interview he said: "The Sensorama may have been too revolutionary for its time" ("Media Art Net | Heilig, Morton: Sensorama", n.d.). Another milestone was in1961 where two engineers of the Philco Corporation invented the first fabricated HMD called 'Headsight'. It was anticipated for telepresence setups just like dangerous military situations and was able to head track via a remote camera. After publishing the 'The Ultimate Display' in 1965 Ivan Sutherland took a further step towards his vision of an ultimate display and created the 'Swordof Damocles' three years later. It was widely considered to be the first HMD system (cf. Steinicke, 2016, p. 25 ff.) It was tethered to a computer, enabled stereo images and it was possible to track head movements. Nevertheless, the HMD was really heavy and therefore did not provide a comfortable user experience. Nearly at the same time in 1968 Thomas A. Furness III introduced the first VR based prototypes for flight simulation which got named 'Super Cockpit'. He is also known as one of the 'grandfathers of VR' and later founded the HIT lab (cf. ibid. p. 28 f.).

Figure 8: Sensorama, Morton Heilig (1962).

In the early 1990s VR already had a short flourishing time with progress and milestones in the technology. "The academic interest in the potential of VR was enormous." (ibid. p.6). And it was also the time where famous movies like 'The Lawnmower Man' (1992) and 'The Matrix' (1999) got released and the time where Jaron Lanier formed the terminology of VR. 1995 Nintendo developed the 'Virtual Boy', the first portable console ever, that was able to display 3D graphics. But the lack of colors and software support as well as the uncomfortable way of using the console lead to a ceasing of the production in the following year (cf. ibid. p.30).

Even though there were great efforts in the field of VR, the technology didn't achieve a breakthrough at that time. VR was really expensive and due to high expectations as well as unfulfilled technical requirements, such as high resolution, limited memory and low latency, the general interest and enthusiasm for VR got lost. Moreover, the limitation of VR games in quality as well as in quantity, and the fact that VR was unavailable for people's homes, got many users disappointed. "The "death of VR" had become a standard narrative" (ibid. p.7 & 15). In the 1990s the general consciousness was moved to the World Wide Web (WWW), the new internet technology and the following smartphone era. Mark Bolas, director of the Mixed Reality Lab at University of Southern California, says concerning the fall of VR "VR didn't bust from my perspective. The VR hype busted" (Robertson, & Zelenko, n.d.). Many people, who already got their interest in VR, still worked on the technology. Especially, for development and research purposes. It was just the public's attention which disappeared.

In a way it can be said that history repeats itself at the moment. In the last two years VR became a subject again and gets more and more public attention. The website The Verge relates to the death of VR back then and the recent coming back with the header "The Rise and Fall and Rise of Virtual Reality" ("The Rise and Fall and Rise of Virtual Reality", n.d). In comparison to the early days of VR there are some important enhancements in technology, such as high-quality graphics, higher resolution, wider field of view, accurate tracking possibilities and leaps in computational power. In addition, the internet makes it easier to share content and web-based distribution facilitates the connection to the consumer. Also open-source software is an apparent advantage and the costs of the technology are decreased. But the main difference today is that VR gets the attention of media and the support of today's major companies such as Facebook, Google, Samsung, HTC, etc. They enforce progress in technology development and they try to get VR to the mass market (cf. Steinicke, 2016, p.15). But even though, it seems to be a better time for VR right now. Only future knows how history will be this time.

2.3 TECHNOLOGY

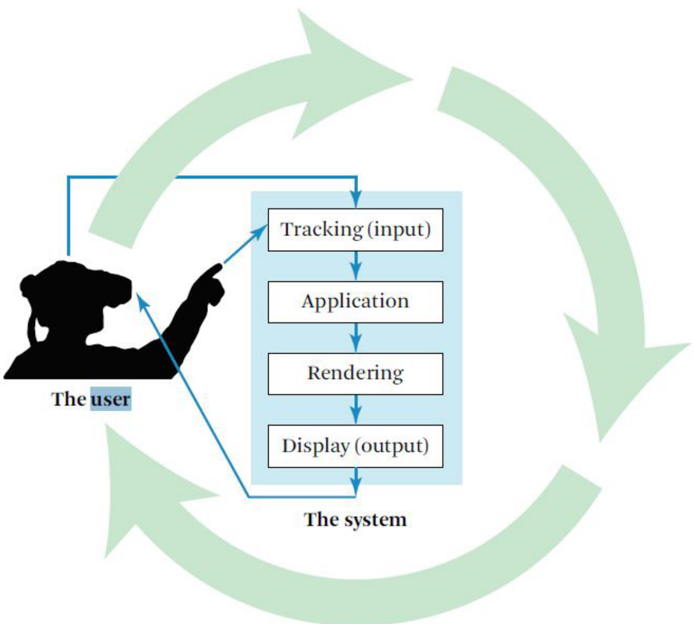


Figure 9: VR system cycle.

A VR system is a computer system which consists of hard- and software to realize a virtual environment which represents a virtual world (Dörner, et al., 2013, p.7). As human and computer system do not speak the same language, there needs to be a translation. Communication between them can be achieved through hardware devices which can serve either as in- or output. What is in- or output depends on how to view it. In the following the direction is considered from user to system. The input describes information travelling from the user to the system, and the output is the feedback from the system which the user receives (cf. Jerald, 2016, p.30 f.). As described in the chapter '3.2 Reality Systems' of the book 'The VR Book' by Jason Jerald, the primary components of a VR system are tracking as input, application, rendering and a display as output (cf. Jerald, 2016, p.31).

The input collects data from the user such as location of eyes, hands or interaction with for instance pressing on buttons. The application describes the "non-rendering aspects of the virtual world including updating dynamic geometry, user interaction, physics simulation, etc" (cf. ibid. p.31). Rendering is the transformation from a format where the computer displays information to a user-friendly format. Visual rendering, as well as auralization (meaning auditory rendering) and haptic rendering (sense of touch) are included (cf. ibid. p.31 f.). As output Jerald defines the user's perception of a physical representation. This could be, for instance, a pixel of a display or sound waves of headphones (cf. ibid. p.32).

2.3.1 BASICS

Now, before going deeper into detail, regarding hardware and software, some basic terms are explained to gain a basic understanding and get familiar with the terminology.

The first term which is examined is depth cues. Depth cues can also be seen as "indicators of distance" (Sherman, & Craig, 2003, p. 119) which help humans to get information about relative distance of objects. There are various ways how humans can receive relative distance. There are monoscopic depth cues, which include techniques that are also used in paintings or photographs to create the feeling of a three dimensional image. Interposition is one cue which is based on our experience because if one object masks another we can possibly be sure that this object is closer. That is how we know it from our normal perception. The same phenomenon occurs with shading. Shadows indicate a positional relation between objects and therefore we can determine how far away an object might be. Other cues can also be size, linear perspective, height in the visual field, meaning how close an object is to the horizontal line, as well as atmospheric effects, such as haze or fog and brightness (Sherman, & Craig, 2003, p. 118 f.).

Besides these monoscopic cues, there can also be stereoscopic image depth cues which are also under the terminology “stereopsis”. Stereopsis is the normal vision of humans and (most) animals. Stereoscopy creates an illusion of depth through the parallax of two different images in each retina of one eye. “This phenomenon is called binocular disparity” (LaValle, 2017, p. 150). The brain perceives both images as one stereoscopic image. In HMDs, the two images also deviate slightly to simulate the Interpupillary distance (IPD), meaning the distance between both pupils, and to provide the spatial vision. In viewing systems the IPD, must be considered because it differs from human to human. At the Oculus Rift, for instance, you can adapt the IPD in some extent (cf. Mills, et. al., 2015). The range of stereopsis is approximately 5 meters (cf. Sherman, & Craig, 2003, p.121).

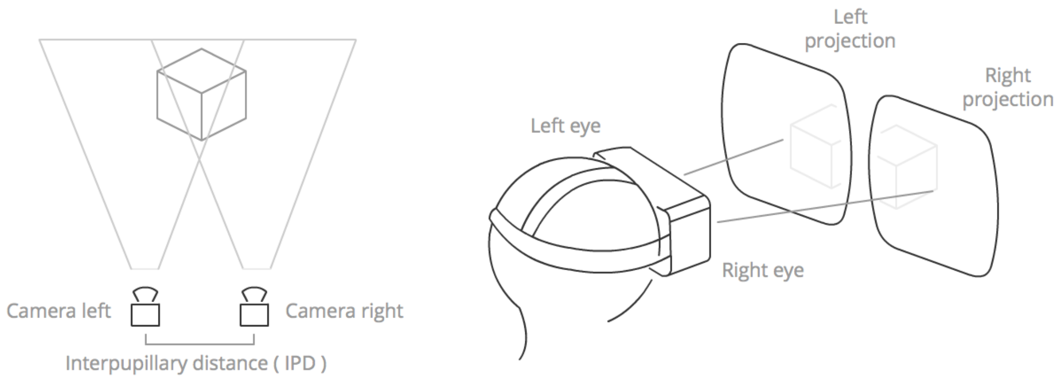


Figure 10: Stereopsis in HMD.

Moreover, depth can also be reached through motion depth cues, for instance, which is based on the fact that objects which are nearer to the eye seem to move more quickly than objects which are further away. And if users move themselves, they receive a proprioceptic feedback how far they moved (cf. Sherman, & Craig, 2003, p.120). At least, there are physiological depth cues which result through muscle movements of the eyes. The distance information on how much adjustment through the muscles of the eyes must be made to sharpen objects is called accommodation. The movement to bring objects in the same location on the retina of each eye is called convergence. And here again the muscle movement can provide information of distance. The range of accommodation is limited to 3m which means this cue has lower priority for more far distant objects (cf. ibid. p. 121).

Another term, which should be considered, is Field of View, short FOV. Field of view is necessary to increase the immersion in VR experiences. The wider the field of view, the more presence enabled. The monocular FOV describes the view from one eye from the nose to the side of the head which is approximately 60 to 65 degrees. And the binocular FOV consist of both monocular fields. Combined they have a 200 to 220 degrees area of view including a binocular overlap which is approximately 114 degrees (cf. “Field of

View for Virtual Reality Headsets Explained", n.d.). This overlap is important to perceive stereoscopic images and should not be smaller than 30 degrees (cf. Sherman, & Craig, 2003, p.120). 360 degrees FOV is not necessary to display for immersive experiences. About 100 to 120 degrees are needed to cover a reasonable portion of human visual range (cf. ibid. p.129). In the following illustration (cf. *figure 11*), you can see that rabbits nearly have the ability to see their environment in 360 degrees, whereas humans have only a 200 to 220 degree field of view.

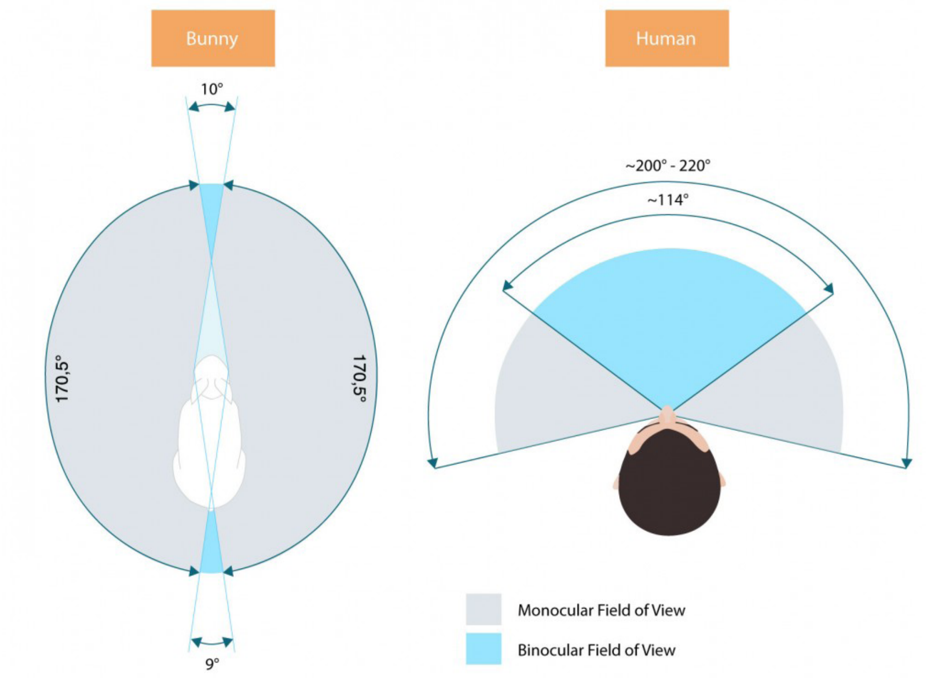


Figure 11: Comparison of the FOV of a rabbit (left) and a human (right).

The next subject concerns how lenses work for VR headsets. *Figure 12* shows the normal perception of objects in different distances. "Depending on an objects distance, light rays from that object diverge at different angles when reaching the eye" ("Head-mounted Displays and Lenses", 2016). This is solved through accommodation which means "a ring of muscle around the lens (the ciliary muscle) contracts to make the lens thicker and rounder" (ibid.). In this case the focal distance is between eyes and screen.

In HMDs the screen is really close to eyes (ca. 3-7cm). Like seen in *figure 13*, the eye fails to focus on very close objects and thus an interposed lens between eye and display creates a virtual image which seems further away. The screen is still at the same distance but the lens bends the light rays and reduces the light from the screen to a point where it is possible for the eye to focus it. So it generates a virtual screen, which looks like a farther away display for the eye (cf. ibid.). To get thinner and lighter HMDs Fresnel lenses can be used. Dependent on how they are segmented you get more or less sharper images and more or less scattered light (cf. "How Lenses for Virtual Reality Headsets Work", 2016).

In comparison to the first illustration the focal distance in *figure 13* is considered between eyes and virtual image.

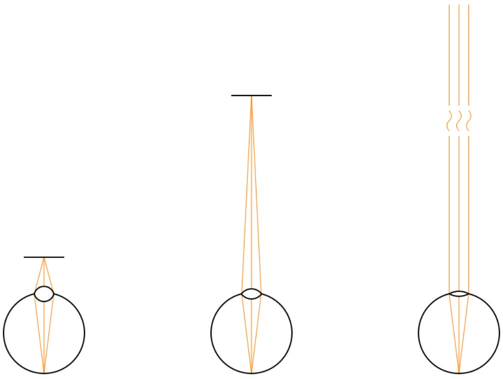


Figure 12: Normal view of objects.

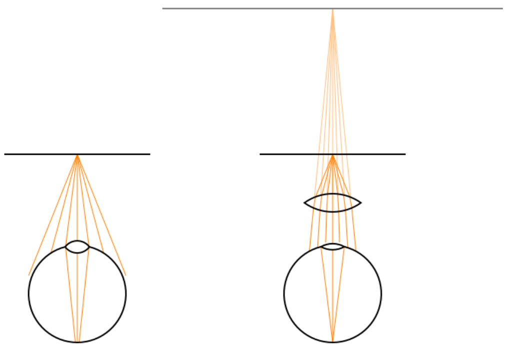


Figure 13: View in an HMD.

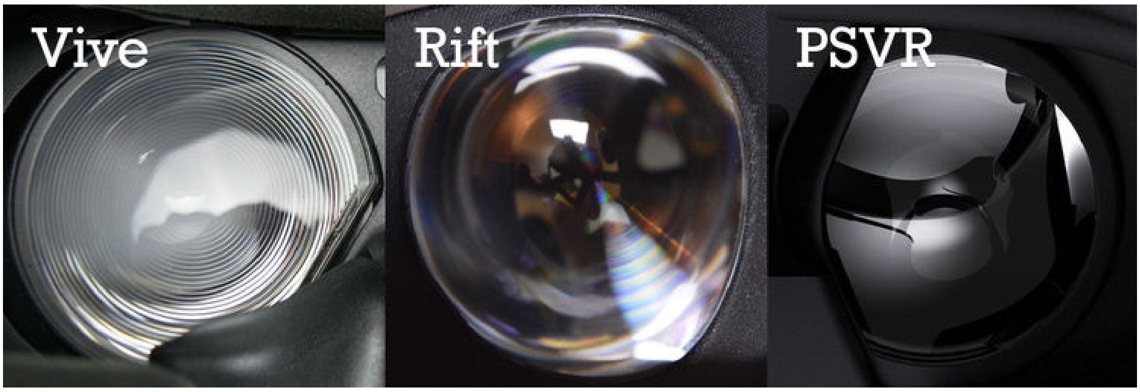


Figure 14: Lens differences of the HTC Vive, the Oculus Rift and the PSVR headset.

Another term which should be explained and not mixed up with FOV is Field of Regard (FOR). Field of regard is explained in the book ‘Understanding Virtual Reality’ as “measure of amount of coverage a given display provides when head motion and other factors are considered” (Sherman, & Craig, p. 130). An HMD has for example 100 percent field of regard because of an unlimited range of motion. In comparison to that, a stationary display often has less than 100 percent FOR. Therefore, the field of regard is not dependent on the field of view. An HMD can have 100 percent of FOR, but still have narrow field of view because you are able to look all around you (cf. ibid. p.129).

The next term which should be explained is latency. ”Latency is the time a system takes to respond to a user’s action, the true time from the start of movement to the time a pixel resulting from that movement responds (Jerald, 2009)“ (Jerald, 2016, p. 183). So to say, latency is the lag time between the user’s action and the virtual environment (VE) displays reaction to that action (cf. Strickland, 2007). Most of the times latency occurs when a user changes his/her point of view and moves the head. For instance, the user already stopped the head movement after changing the point of view, but the image is still moving. This kind of latency is often called Motion-to-Photons latency. But "the term can also be used for a lag in other sensory outputs" (Strickland, 2007). The main issue with latency is that a high latency can lead to motion sickness, instability, and discomfort of the user and has therefore an impact on the sense of presence. But the extent of latency always depends on the user because everyone has a different sensitivity to latency. "[…] things like device, bandwidth, content loading and streaming, and content type" ("Virtual Reality (VR) and 360 Videos 101 — A Beginner's Guide", 2016) can have impact on latency. So the goal for VR is to keep latency down to provide a better visual flow and to preserve the immersion. In an Interview Fred Brooks, American computer architect and computer scientist, states that the latency for VR should be under 20 milliseconds and preferably below 12 milliseconds (cf. Pinson, 2016).

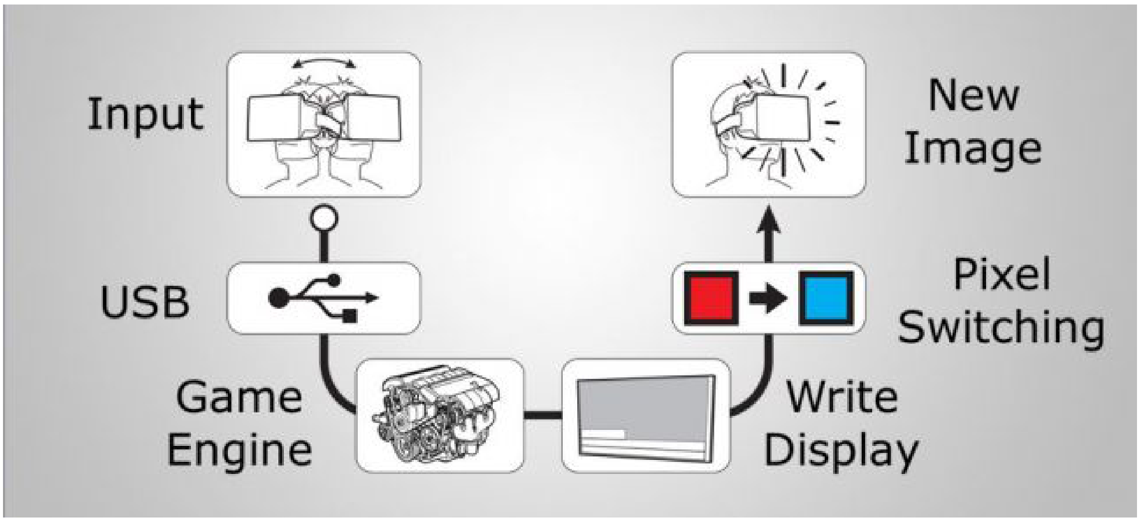


Figure 15: Motion-to-Photons latency.

The last terminology, which is highlighted, is called Degree of Freedom (DOF). Degrees of Freedom can be seen as a measurement for the ability to move around in space (cf. Snyder, 2016). The ultimate goal is to reach 6 DOF in three dimensional spaces of body movements.

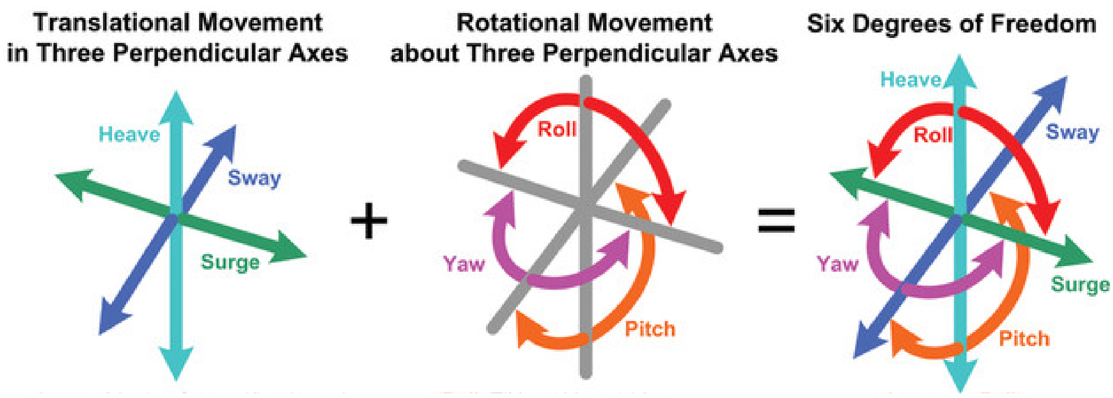


Figure 16: 3 DOF + 3 DOF = 6 DOF.

Just to have an imagination of DOF, a hand requires the tracking of 22 movements and has therefore 22 DOF (cf. Sherman, & Craig, 2003). For a true VR experience you will therefore need three DOF, generated through translational movement, which means moving along the x, y and z axis and three DOF, generated through the three rotational movements roll, yaw and pitch (cf. Snyder, 2016).

2.3.2 HARDWARE

2.3.2.1 OUTPUT

Output devices are considered as visual displays, speakers, haptics and motion platforms. To address other senses there can also be more uncommon displays with olfactory, heat, wind or even taste (cf. Jerald, 2016, p.32).

There are several kinds of visual displays. Stationary displays could be amongst others, curved screen projections or so called CAVEs (Cave Automatic Virtual Environment). These systems were first developed at the EVL (Electronic Visualization Laboratory) at University of Illinois and premiered 1992 at the Siggraph computer graphics conference in Chicago (cf. Sherman, & Craig, 2003, p. 143). CAVEs surround the user with large projection screens. There are rear-projections on the walls and a down-projection on the floor. The person is tracked via a motion capture system and can also see stereo with special LCD stereo shutter glasses that separate alternate fields going into the eyes (cf. Kenyon, 1995). Interaction is also provided through, for instance, handheld props, voice commands or even through vehicle platforms (cf. Sherman, & Craig, 2003, p. 102). CAVEs and screen projections are more suitable for a crowd of people in comparison to a head-mounted display. But they also need more space. So it is important to select the appropriate hardware for the desired case (cf. Jerald, 2016, p. 32).

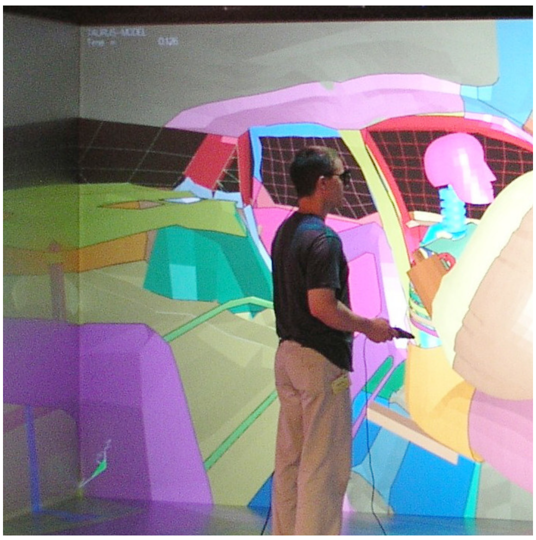


Figure 17: CAVE example no.1.

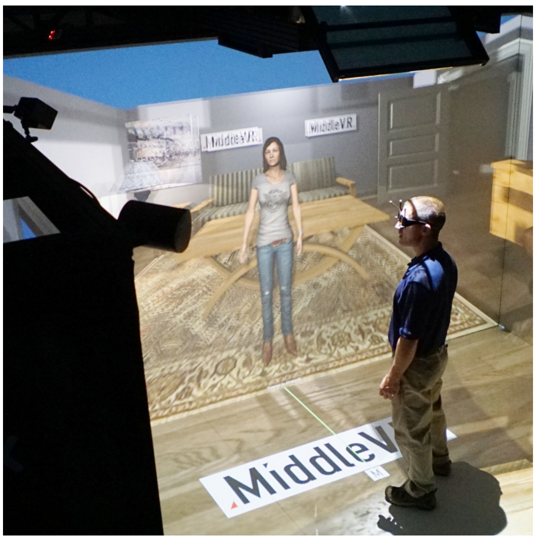


Figure 18: CAVE example no.2.

HMDs are head-based projections. They are the primary output devices for VR. Generally they consist of a headset with two lenses, a display, which provides two stereoscopic images, outside material to block out distractions. Some headsets also have several sensors to track movement or two earpieces included. Through an HMD, a user can adjust to a VE and the sensors provide that the movement in this environment is according to the users' normal movements.

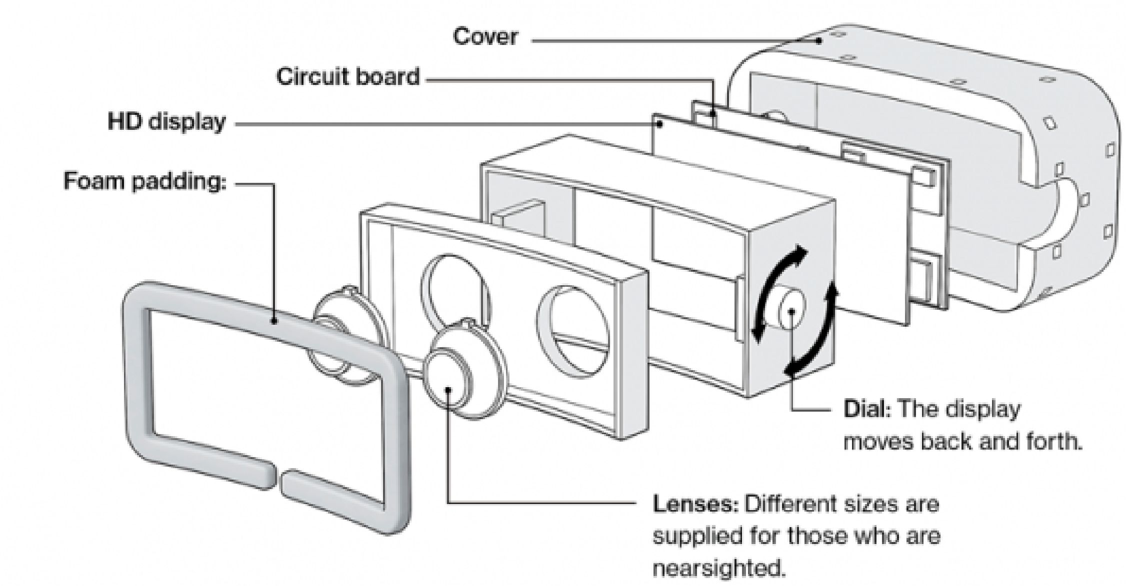


Figure 19: HMD (Oculus RIft) exploded view of MIT.

There is a difference between mobile VR and room-scale VR headsets. The HMDs that are used with the phone relate to the terminology 'mobile VR'. The smartphone acts like the VR display and can be attached to the VR mount, which incorporates two lenses to provide stereoscopic vision. Mobile VR headsets have no environment requirements and no wires are needed. In comparison to room-scale VR headsets, they do not contain positional tracking. So they only provide three DOF, only the rotational tracking. Therefore, you can only stay at one position and watch the content from different angles (cf. Mills, et al., 2015).

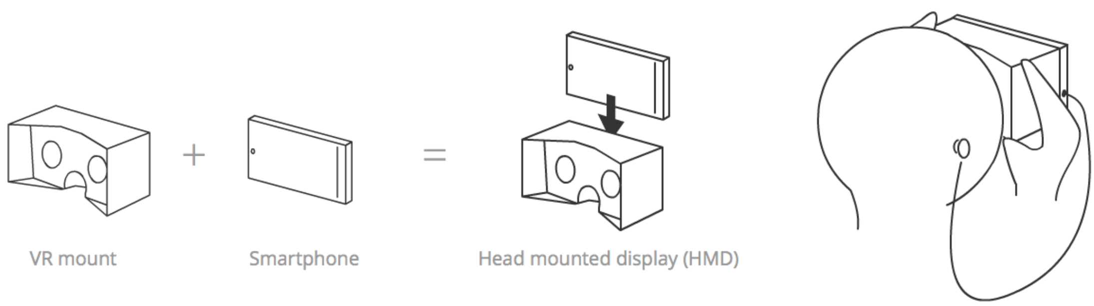


Figure 20: 'Mobile VR' - setup.

The low cost way to experience VR came with the release of the Google Cardboard in June 2014. It consists of two lenses which provide stereopsis and a cardboard mount in which you can place your smartphone. Even if there is a controversy about whether Google Cardboard can be designated to 'real VR' it is still 'basic VR' technology which enables everyone with a smartphone to experience a form of Virtual Reality (cf. Smith, 2015). Therefore, it can be seen as 'gateway drug' to bring VR to the masses (cf. Dotson, 2016). "Mobile VR is driving cultural awareness of the technology because it's the most accessible and the most democratised" (Bennett, 2016), said Norman Wang, VR expert from Opaque Media. And the success of Google cardboard can be seen in their sales figures. End of February 2017 Google announced that they shipped over 10 million Cardboards so far (cf. Singh, 2017).

Another mobile VR headset is the Samsung Gear, which got released in November 2015 and is powered by Oculus. Here again the smartphone screen is acting like a stereo display, uses Oculus head-tracking tech in combination with smartphones (Android). In comparison to Google cardboard, which only uses the gyroscopic sensors and positioning systems of the smartphone (if it contains one), the Gear has additional integrated external sensors to track head movements (cf. Lamkin, 2017). Moreover, the Gear is more comfortable in wearing and provides soft foam padding as transition from headset to head. Additionally you do not have to hold the HMD in your hands, it can be applied to your head via mount. The Gear can only be used with Samsung smartphones and the "visual experience of using Gear VR will depend on which Samsung smartphone you use" (Lamkin, 2017).

Google's Daydream View was released in November 2016. Similar to the Samsung Gear it only allows special phones to get used, such as the 'Axon 7' from ZTE, 'Google Pixel' or the 'Moto Z' from Motorola (cf. "Daydream – Smartphones", n.d.). But Google tries to expand their compatibility with other phones as well. Furthermore, the distribution VR platform 'Daydream' is available as app and enables viewer to watch 4K VR experiences, which is a good quality (cf. "A Beginner's Guide to Tethered & Untethered VR Headsets", 2016). The Daydream View also offers a comfortable design and material and it is claimed by Google that "View is 30% lighter than other mobile headsets on the market" (Lamkin, 2017.). "We're really excited about simplifying the technology, simplifying the usability, making it understandable for anyone, so that they can understand why it would fit their life" (Mokey, 2016), said the product manager of Google's Daydream View Andrew Nartker. All in all, you can say that the goal of mobile VR is to bring Virtual Reality to the consumer in an affordable way.

Besides mobile VR headsets, there are room-scale VR headsets with build-in-screens. They display visuals for both, the right and the left eye to provide stereopsis. Room-scale HMDs still need to be tethered to a computer, but maybe that will improve in the future. In addition they provide positional and rotational tracking (cf. Mills. Et al., 2015).

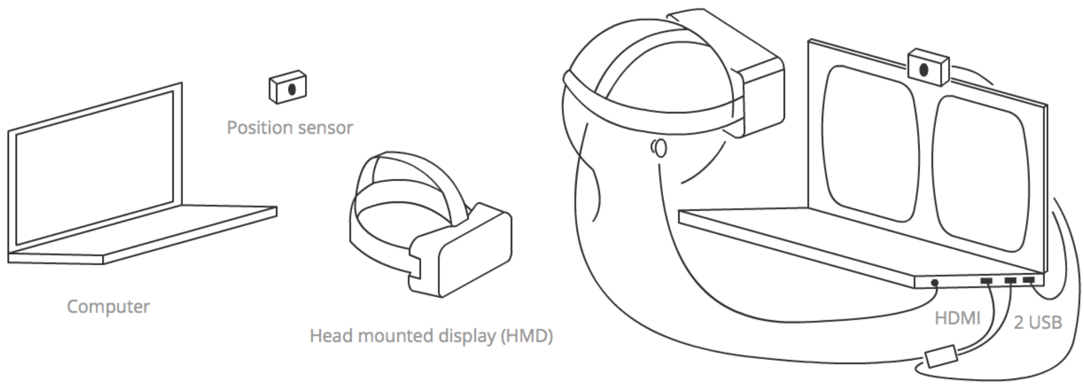


Figure 21: 'Room Scale VR' - Setup

The Oculus Rift started 2012 as a Kickstarter project by Palmer Luckey, a 16 year old boy who got interested in VR technology and developed his own VR prototype. Through collaboration with the famous American game programmer and the co-founder of Id Software John Carmack his project gained more and more attention and improvement in development. In March 2014, Oculus was bought by Facebook for approximately two billion dollar (cf. Kovach, 2014). So, the Oculus Rift can be seen as trigger for the following 'VR hype' (cf. "Oculus Rift History - How it All Started", 2015). Until now, there were three versions of headsets released: DK1 (Developer Kit 1) and DK2 and the last one which got released November 2016 is the consumer edition CE1. The Rift works with a camera tracking system which is tethered to a computer. Since end of 2016 Oculus also provides controllers known as Oculus Touch (cf. "Oculus Rift", n.d.).

The Vive got released April 2016 and is one of the major competitors of the Oculus Rift. There is cooperation between HTC and Valve concerning this HMD. Valve as game developer and digital distribution company supports the software as well as supervises the distribution platform of the Vive which is Steam (cf. Porter, 2017). The Vive is the most expensive possibility to experience VR at the moment, but at the same time it is one of the best overall experiences. The Vive includes two base stations with the Lighthouse tracker system, a headset and two controllers. Concerning room-scale and play arena, the Vive definitely provides most of the space in comparison to other VR systems at the moment (cf. Davies, 2016). It supports a higher 'sense of presence' because you are able to move freely in the VE.

The PlayStation VR (PSVR) does not require a PC, but instead, it works with the PS4 console. In comparison to the other two room-scale VR headsets, it has two cameras for stereo depth perception. Good head tracking and a responsive refresh rate are offered and with 120 frames per second it also gives a smoother image (cf. Davies, 2016). At the same time it is one of the more affordable solutions, but the PS4 controllers and the needed cameras are not included in the package with the headset and sold separately. The PSVR got released in October 2016 and provides a lot of game experiences in the Sony Library (cf. Porter, 2017).

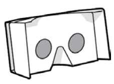
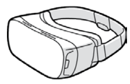
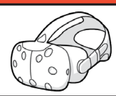
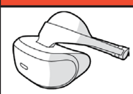
VR headset	Cardboard	Gear	Daydream	Rift	Vive	PSVR
						
Manufacturer	Google	Samsung	Google	Oculus	HTC	Sony
Display	compatible phone	compatible phone	compatible phone	OLED	OLED	RGB OLED
Resolution	dependent on phone	2560 x 1440 px.	dependent on phone	2160 x 1200 px.	2160 x 1200 px.	1920 x 1080 px.
Resolution per eye	dependent on phone	1280 x 1440	dependent on phone	1200 x 1080	1200 x 1080	960 x 1080
FOV	100°	101°	90°	110°	110°	100°
Experience	3 DOF	3 DOF	3 DOF	6 DOF	6 DOF	6 DOF
Refresh Date	-	60 Hz	60 Hz	90 Hz	90 Hz	90-120 Hz
Compability	wireless	wireless	wireless	PC	PC	Console
Weight (without phone)	76g	318g	218g	470g	555g	610g
Release Date of first version	June 2014	Nov. 2015	Nov. 2016	Sep. 2014	April 2016	Oct. 2016
Price	ca. 15$	ca. 70$	ca. 80$	ca. 600$	ca. 800$	ca. 400$

Chart 1: Comparison of HMDs, adapted from different sources provided in the appendix.

Another output device is a speaker which optimally provides spatial audio. Spatial audio gives the possibility to hear from which directions sounds are coming in a three-dimensional space. The audio can be fixed in space or the user can take headphones to better block out the outside world and thus support the immersive experience (cf. Jerald, 2016, p.34 ff.).

Haptic controllers are another output device that contributes to full immersion. Haptic systems are systems that give a user force feedback and touch interaction (cf. Strickland, 2007). Jason Jerald describes haptics in his book 'The VR book' as "artificial forces between virtual objects and the user's body" (Jerald, 2016, p.36). The haptic feedback can result through different forms such as vibration, pressure or temperature (cf. LaValle, p.43). Devices, which can function as haptic controllers, are data or exoskeleton gloves or normal hand controllers (cf. Jerald, p.36 ff.).

If real world locomotion is not possible because of space issues, treadmills can be the solution. With treadmills you can walk or even run while staying in one position. Harnesses are allocated to keep user inside of the platform. The most common examples on the market are the Virtuix Omni (cf. *figure 22*) and the Cyberith Virtualizer (cf. *figure 23*). Other more extraordinary output devices can be olfactory displays with pumps which spray odors for the sense of smell. And to address the taste senses there are researches concerning gustatory interfaces (cf. LaValle, p.370 ff.).

Figure 22: Virtuix Omni.

Figure 23: Cyberith Virtualizer.

2.3.2.2 INPUT

Some devices can be input as well as output device. For example, controllers, which function as input device through a pressed button or a tracked position, can at the same time be an output device which gives the user a haptic feedback. For VR experiences it is necessary that position and orientation of the sense organ are tracked to adapt the stimulus (cf. LaValle, p.44). Sensors are "devices that extract information from the real world" (ibid. p. 42). They are used to provide DOF in the VR experience and are responsible for the internal tracking systems. There are mainly three kinds of sensors which are used for VR: gyroscopes, accelerometer and magnetometers. For the orientation part there is usually an Inertial Measurement Unit (IMU) used. Its main component is a gyroscope which “measures its own rate of rotation; the rate is referred to as angular velocity and has three components” (ibid. p.44). Gyroscopes integrate measurements over the time to be able to estimate the cumulative change in orientation. Because this can lead to a so called ‘drift error’, other sensors like an accelerometer and possibly a magnetometer are used to counteract. IMUs can easily be integrated in wearable devices because they are small, light and not expensive because they are also produced for the use in smartphones (cf. ibid. p.44). “They are one of the most important enabling technologies for the current generation of VR headsets and are mainly used for tracking the user’s head orientation” (ibid. p.44). Besides, IMUs digital cameras also provide a good source of information for tracking systems. Due to the smartphone industry, they are portable and increasingly cheap and provide improving quality (cf. ibid. p.44).

The body tracking is also needed to track the user in within the play area. Body tracking concerns only the room-scale VR systems, such as HTC Vive, Oculus Rift or PSVR. The Vive VR system has a special system that uses lasers using IR LED for positional tracking and is called Lighthouse. At this system an omnidirectional flash is send out from two base stations (one vertical, one horizontal). The position of the HMD can be determined through time differences, how long it took the laser to strike a sensor on the HMD. In combination with the IMUs on the headset the Vive provides a low tracking latency. And due to the use of laser the tracking can be very precise even at long distances. Therefore the Vive has the largest play area which could be even larger if more than two base stations would be supported (cf. Davies, 2016). The Oculus Rift works with a camera system which is connected to your PC to track the body. The Oculus HMD is covered in 44 IR LEDs which are placed all over it (front, back, sides, top and bottom). If you look at the headset, they are invisible, but the IR can pass through the fabric cover. So the camera can see the position of the LEDs and therefore recognize a pattern of lights which allows determining orientation (cf. ibid.). “How large the LEDs appear on camera helps determine how far away the headset is” (ibid.). The special thing about Sony is that they use two cameras for stereo depth perception and it uses the existing PlayStation Camera for positional tracking. Same as the Oculus Rift, LED (others than IR) lights are tracked on the HMD and again a pattern covers the whole headset for 360 degree tracking. In comparison to the Rift the PSVR headset has only 9 LEDs, “but they are shaped in such a way that their orientation can be determined by the camera, and the stereo depth perception can work out their position” (ibid.). In *figure 24* you can see the different room-scale areas of several VR systems. As you can see the Vive VR systems with its Lighthouse tracking system provides most of the possibilities in space whereas the play arena of the Oculus VR system as well as of the PlayStation VR system is much narrower.

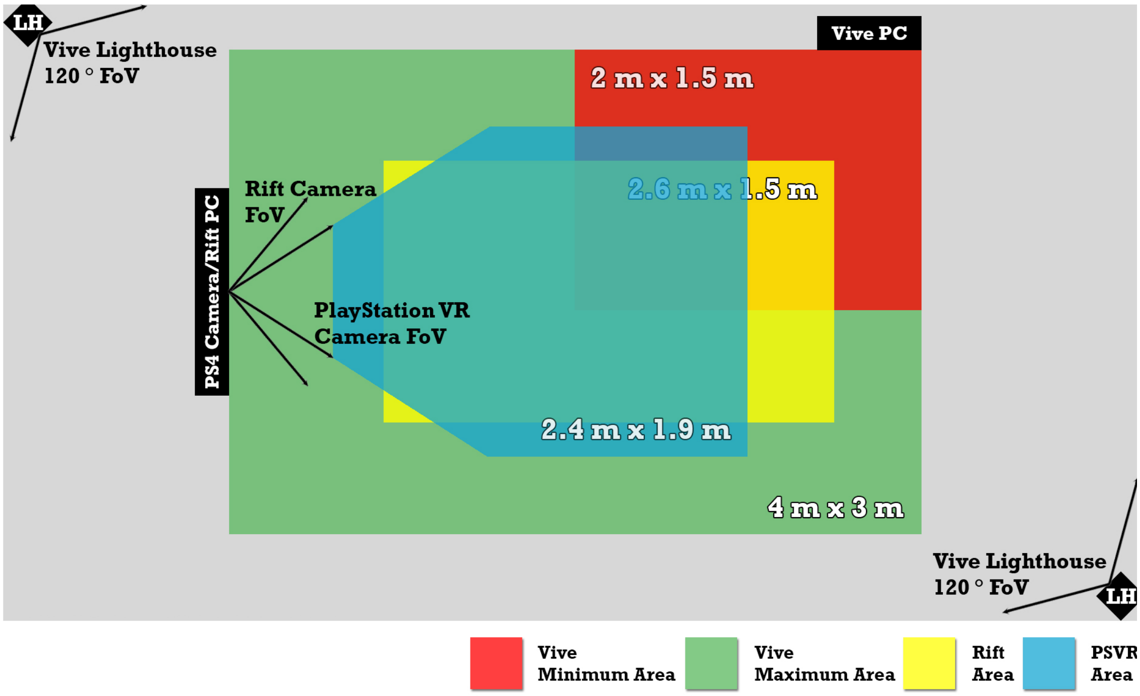


Figure 24: Comparison of play areas of HTC Vive, Oculus Rift and PSVR.

Gesture recognition is often made through hand-held input devices, such as controllers or via smart gloves. They provide, for instance, that you can see your controllers or your hand in the VE. Sensor based input devices also "use accelerometers, gyroscopes and various other micro-electro-mechanical systems for movement measurement and processing" (Eisenberg, n.d.). Gloves on the other hand can ensure more accurate movements, rotation and position of the hands and even detect the bending of the fingers. For that, wires with several inertial and magnetic tracking devices are used (cf. ibid.).

Besides body tracking, eye tracking, as well as voice recognition and physical input through for example buttons, switches, valuators or props can serve as input device which gives information from the user to the system. Further information to this subject can be found for instance in the book 'The VR Book' from Jason Jerald in part V Interaction.

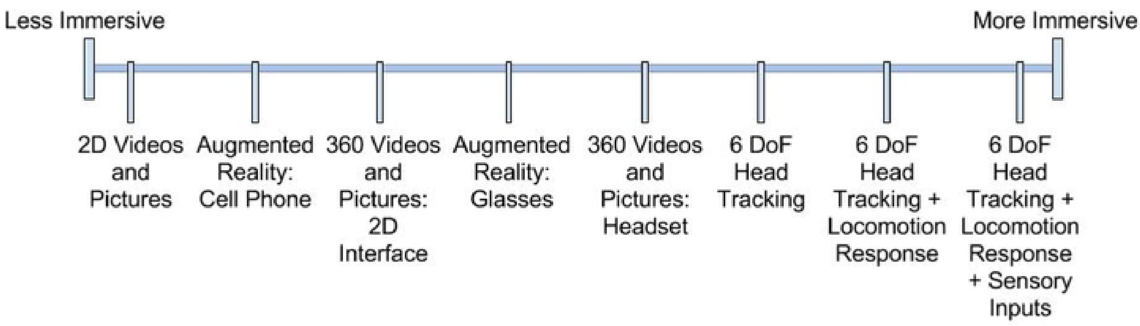


Figure 25: Different stages of immersion depending on (VR) system. You can say, the more tracking and DoF is provided, the more immersive the VR experience can be.

2.3.3 SOFTWARE

There are three major game engines that can be used to create Interactive VR experiences. These are Unity, Unreal Engine and Cryengine. In the following, there will be a short description of each. Unity is good for mobile based VR games and supports mobile, desk, web and console platforms (cf. Eisenberg, n.d.). Moreover, Unity is supported by the official Oculus Rift SDK what means, you can develop and publish content for the Oculus Rift without having to pay anything but the hardware (cf. "What are the best game engines for Virtual Reality development?", n.d.). In comparison to other engines, there is no source code accessible for Unity, but there is a wide developer community which is keen on supporting every developer. Programming languages that are supported are C#, Uniscript and Boo. Unity provides two versions, one free license where all common mobile platforms are supported and one pro version which also support Xbox360, Nintendo Wii and PlayStation (cf. Eisenberg, n.d.). Unreal by Epic Games is more suitable for console-based VR games. It is known for "high powered games with exceptional graphic and features overall" (ibid.). It supports PC, console, mobile and VR platforms (cf. Takahashi, 2016). Unlike Unity the full source code of Unreal is available and developers can amend it if necessary. It includes C++ as scripting language and is completely free (cf. Eisenberg, n.d.).The Cryengine by Crytek also supports VR headsets such as the Vive and the Oculus Rift, as well as PC and console (cf. Lundgren, 2016). In addition, Crytek's dedicated VR development team is one of the largest in the industry" (Mendoza, 2016) and has a pay-what-you-want business model. The source code is available and supported script languages are C++, C# and Lua. "We want to experience a simulated world that feels real. That's the expectation of VR" (cf. Takahashi, 2016) said Frank Vitz who is a creative director at Crytek.

Besides the engines that are needed for interactive VR experiences, the software development kits (SDKs) from the relevant HMDs, such as for instance Oculus Rift or HTC Vive are used. Also classical 3D software, such as for example Autodesk Maya or Foundry Mari, is utilized for the purpose of creating VR experiences.

2.3.4 360 DEGREE CAMERAS

Due to VR gets more popular and more content is generated, the market for cameras that capture 360 degrees is increasing. Meanwhile, there are a few cameras on the market which have different price ranges for different end consumers and purposes.

One of the starter level cameras, which is also suitable for the normal consumer, is the Ricoh Theta S which is available under 400$. Due to the small size and its compactness the Ricoh Theta S is easy to carry around. The camera is accompanied by smartphone apps which allow reviewing footage on your mobile. One of the extra features of the Ricoh

Theta S is the possibility of livestream while shooting. Due to these features this camera is also a good choice for getting to know the new medium and also for previsualization of 360 degree VR projects as well as for a proof of concept or scouting (cf. Rhodes, 2016). It is definitely an affordable option and offers 25 minute capture and 30 frames per second (cf. "Product | RICOH THETA", n.d.).

In the mid-range class there are consumer grade rigs, such as for example the GoPro Omni, which costs around 5000$ (cf. "GoPro - Virtual Reality", n.d.). It consists of six synchronized GoPro HERO4 cameras which are attached on a portable spherical rig. All in all, they are able to capture 8K resolution. The software GoPro Kolor comes with the GoPro Omni and allows an easy way to import, stitch, view and publish content. There is no live preview or real time stitching possible, but combined with a Ricoh Theta S you could also get a quick preview on set (cf. Rhodes, 2016).

One of the high-end pro VR rigs, which is a professional option, is the Nokia Ozo. It is a spherical camera with eight synchronized sensors. The Nokia Ozo provides live stitching and preview through the Ozo software, captures 6K and allows 45 minutes of 360 degree capturing at 30 frames per second (cf. "Nokia OZO | Technical specifications", n.d.). You can also adjust sensors and it includes a well-designed end to end workflow for VR. The costs are around 45000$ (cf. Rhodes, 2016). Custom rigs that are built around cinema cameras, such as for example Blackmagic, RED or ARRI cameras with fisheye lenses, deliver the best quality. With this solution a lot of experimentation is required and it is the most complicated way to capture 360 degree content in comparison with other cameras. But on the other hand, you get a high resolution and really good quality which is necessary for a good user experience. Five RED weapons cameras can capture 10K at 60 frames per second. Moreover, you have a control over exposure and lenses, so you can modify the rig to your goals of production (cf. ibid.). There are several cameras available in every category and there will be more in the future. In the end everyone needs to decide what kind of cameras suit the project and what category of 360 degree cameras is the best solution.

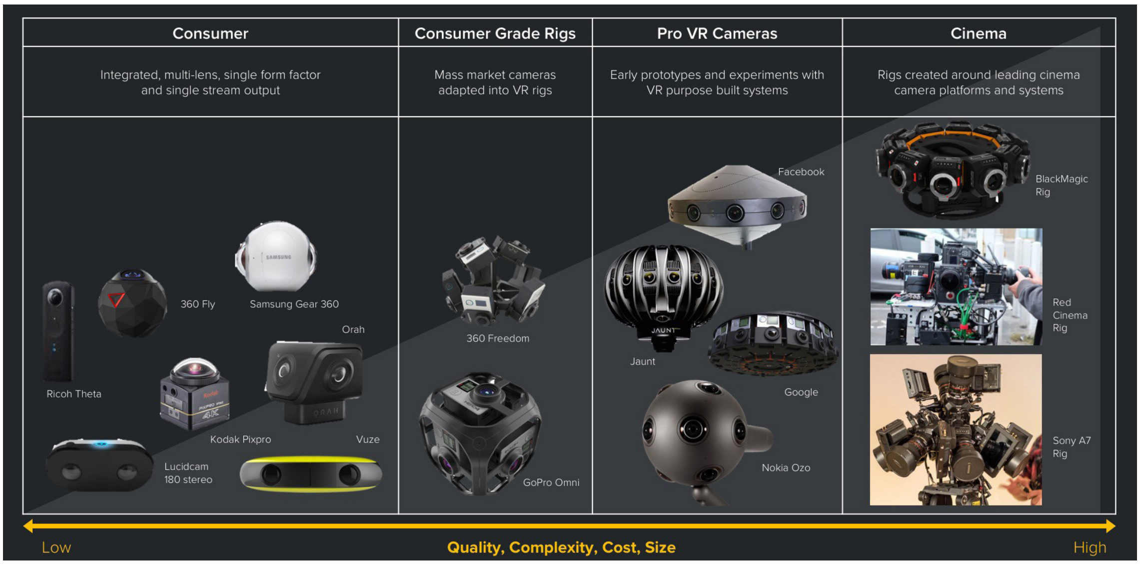


Figure 26: Camera gamut. Pixvana.

All the described cameras where designed for monoscopic capturing. But capturing in stereoscopic 3D can add depth data to the image and lead to another level of immersion. But there are some issues that come along with stereoscopic capturing and 360 degree videos. On the one hand stitching gets really hard because you have more cameras with left and right view and on the other the quality is a problem with stereoscopic VR. “People that are resolution-picky will probably prefer monoscopic videos, which can have twice the resolution of stereo videos. The stereo effect may not be worth anything to you if you can’t get past the blurring” (Rowell, 2015), explains Oculus CTO John Camarck. There are some stereoscopic cameras on the market, for instance the Vuze Camera, or Panocam 3D, but they are also only available for consumer standards and not possible to capture high-quality stereoscopic content.

So due to issues with stitching and bad quality, a lot of content creators prefer capturing monoscopic 360 degree video. But there will be further development and research in this field and maybe, if technology and resolution emerge, stereoscopic capturing will be a solution in the future. One first step is the so-called “Jump” camera system, which got represented 2016 from Google. It is a “practical system for capturing high resolution, omnidirectional stereo (ODS) video suitable for wide scale consumption in currently available virtual reality (VR) headsets” (Anderson, et al., 2016). It is a less parallax prone system which uses a GoPro Odyssey camera rig which consists of 16 GoPros for capturing and “fully automatic stitching pipeline capable of capturing video content in the ODS format” (Anderson, et al., 2016). As ODS is possible to store in a traditional video format, it is an advantage for post-production, as well as streaming and playing back on mobile devices (cf. Agarwal, 2016). ODS allows the viewer look in any direction with a seamless projection which provides 360 degree and stereoscopic 3D (cf.ibid.). “The whole ecosystem surrounding the GoPro Odyssey rig and Google’s Jump-platform is an incredibly impressive and forward thinking one” (Hoffmeier, 2016).

Figure 27: GoPro Odyseey used for Google Jump.

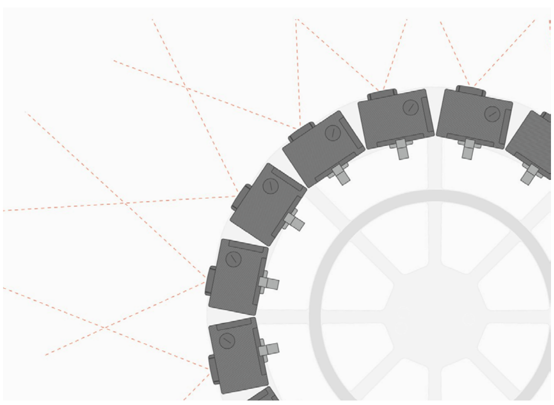


Figure 28: Capturing of the Rig.

2.4 APPLICATIONS

VR can be seen as new human-computer interface where you can act like in the real world and still interact with a computer program. You can say that VR improves the human interaction with computer systems (cf. Dörner, et al., 2013, p.15). Moreover, VR provides better possibilities to visualize content. For instance, not everyone is capable of imagining 3D construction plans, but with VR it could be easy visualized and you are able to watch them from all angles in 3D space. For example, Disneyland in China was designed in VR (cf. Gaudiosi, 2015). Also prototypes of cars or other machines can be built close to reality, tested or configured by the consumer in VR. VR is possible for many applications in a lot of different sectors. It "successfully deployed in various industries for many years now" (Jerald, 2016, p.12). Besides oil and gas exploration, VR is also utilized in "scientific visualization, architecture as well as in flight simulation, therapy, military training, theme-park entertainment, engineering analysis, and design review" (ibid.).

Especially for education and training VR is an important tool that could be more and more important in the future. Edgar Dale's 'Cone of Experience' (cf. Jerald, 2016, p.13) from 1969 reveals how important for memory it is to do and experience things instead of just reading.

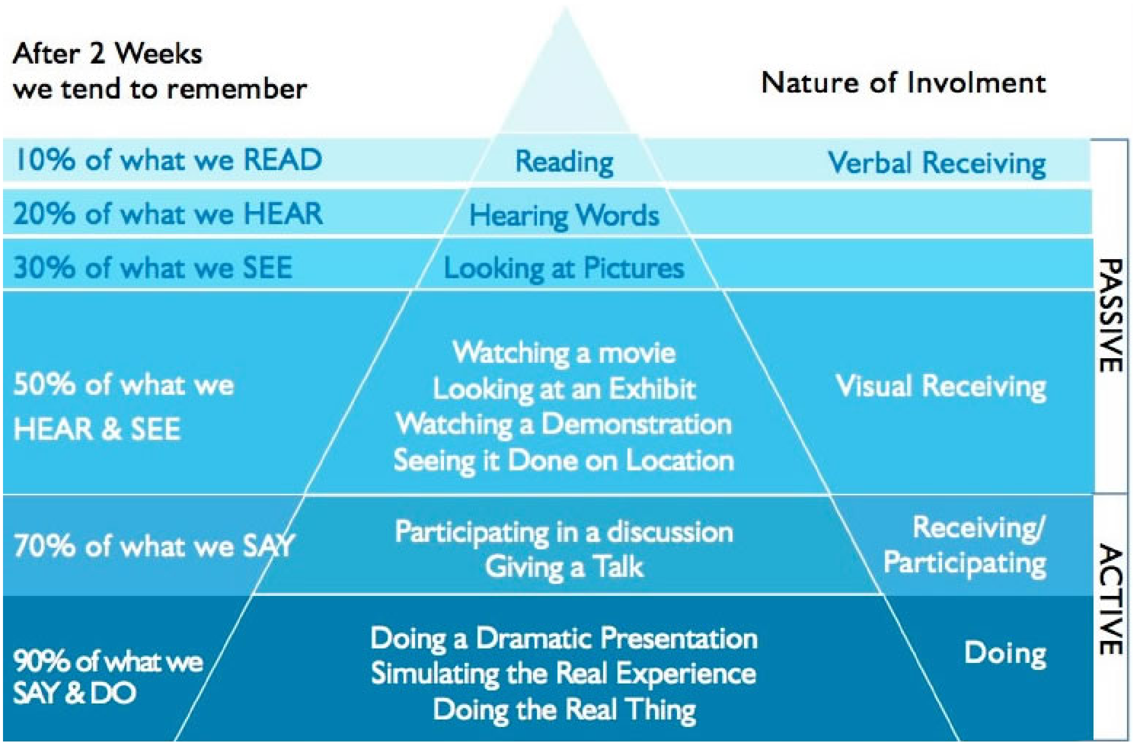


Figure 29: Cone of Experience/Learning. Edgar Dale (1969).

Compared to what we read, where we remember approximately 10 percent of the read content after two weeks, doing provides about 90 percent of remembrance. "Memories are embedded with location" (Chocano, 2014). This Statement of Professor Mark Bolas, Director of the Mixed Reality Lab at USC, underlines the theory of Edgar Dale concerning the 'Cone of Experience'. And VR provides a level of learning and training which allows you to experience things and feel present at places. It can be for example useful for school field trips or trainings with dangerous or sensitive technology and expensive equipment.

Also in medicine, VR has several application possibilities. One of them is pain and fear management. In Virtual Reality people can face their fears in a safe and controlled environment, such as for instance confronting veterans with posttraumatic experiences or people with phobias (cf. "7 ways Virtual Reality is changing healthcare and medicine", 2016).

In entertainment the video game industry is still the biggest in the VR sector. But VR expands to music, sports and other events. There are several 360 degree YouTube music videos and the company NextVR specialized on live concerts or live sports events such as NBA Games or other major leagues where the users can be 'live' at their favored concert or match (cf. News | NextVR, n.d.).Theme parks, like the Six Flags in Texas or the Europapark in Germany also use VR technology to provide a different rollercoaster experience with content in a VR headset (cf. "The New Revolution Virtual Reality Coaster", 2016/ "Alpenexpress Coastiality", n.d.). Last year the first VR series 'Invisible' by the Bourne Identity director Doug Limon got launched and there are also other announcements of VR projects in combination with famous directors such as Steven Spielberg or Alejandro Iñárritu. Moreover, there are VR cinemas opening all over the world, such as the first permanent VR cinema in Amsterdam or the MK2 in Paris. Film companies use short VR 360 degree previews of their movies as promotion. 'Jungle Book', 'Assassin's Creed' and Disney's 'Pete's Dragon' are good examples for 360 degree VR experiences to promote the film. And also museums use VR nowadays to allow the visitors understand certain topics in a better way through 'visiting' places in a virtual world. There is even a VR experience (Woofbert: VR) which allows stepping into artworks and paintings presented in a virtual museum (cf. Kim, 2017).

Figure 30: Six Flags VR experience.

Figure 31: Woofbert VR App.

Besides that VR is also a good tool for advertising. VR is great for providing 360 degree views of products, virtual environment tours or to configure products. Users can experience the products before buying them. This can also be a good application for travel agencies and real estate industry.

Another scope can be the social part of VR which is right now pushed from Facebook. At the moment there are a lot of VR experiences which are isolated, but that will possibly change in the future. VR provides the opportunity to overcome geographical boundaries and enable face-to-face communication in a virtual room. “It’s like having a collaborative lucid dream” (cf. Kelly, & Heilbrun, 1989), said Jaron Lanier 1989 in an interview for the ‘Whole Earth Review’ magazine. But this application area is not fully developed yet.

Journalism in 360 degree with VR as medium is also an emerging field and so are a lot of others which are not mentioned anymore at this point.

In the following, there will be focus on how useful VR is as tool for VFX productions as well as how some tools known from the Visual Effects field can be useful and applied to Virtual Reality.

3

RELATIONSHIP

VR AND VFX

"OFTEN AND IN PARTICULAR IN VR, WE LOOK AT THE FUTURE THROUGH IDEAS THAT ALREADY EXISTED IN THE PAST."

– "VR Post Production - Kilograph", 2016

Figure 32: Screenshot of 'Dear Angelica' (2017).

VR is a current subject in the VFX sector and was one of the big topics 2016 at the major conferences such as FMX and SIGGRAPH. Besides Animation and VFX there where a lot of panels around of VR production, pipeline and technology and even this year program of FMX 2017 reveals VR as one of the main topics (cf. “FMX: Program 2017”, 2017). There were also VES (Visual Effects Society) panels about Virtual Reality’s future as well as about VR postproduction which shows that VR is also a topic concerning VFX companies (cf. “Event - VR Post Production”, n.d.). Also known magazines in the industry, such as for instance the German trade-magazine ‘Digital Production’ pick up on the VR field and the February 2017 edition integrates VR and AR as a main topic.

In this thesis, there are three major categories chosen where you can say that VR and VFX converge. Virtual Production gets more and more popular for film and VFX productions and why not using Virtual Reality technology, such as for instance an HMD to allow manipulating the scene in virtual space directly on set? Also VR can be used as tool for realizing VFX content. It is striking that more and more well-known VFX companies get involved in VR as well. So the question arises whether the VFX pipeline suits VR and if it is possible to use Visual Effects in the usual way.

But before being able to deal with these questions it is crucial that some terms are defined clearly for the scope of this work. As already mentioned, there is no standardized definition for VR yet and so, also forms and sub-categories are not defined yet. Moreover, there are a few terms which might be interpreted by everyone in different ways and have other meanings, so they need to be defined for the following work.

3.1 CONTROVERSY ABOUT THE TERMINOLOGY

There is a controversy going on about the definition what ‘real VR’ content really is. Like VFX supervisor Keith Miller states in an interview: “We’ll continue to see a blurring of the lines between categories of VR. There’s a lot things being called VR now” (Cook, 2016). So there are a lot of different forms of VR circulating at the moment. And often there is the discussion among the VR community if 360 degree video content can be in fact called Virtual Reality. But even for 360 degree video you must define and make a distinction between different forms of spherical videos. In Facebook or YouTube for instance, it is also possible to watch 360 degree content on your PC in a web-browser and pan around in the scene. At that point you have to be careful with the terminology because this way of viewing 360 degree contents differs a lot and cannot be considered as real VR (cf. “The Cinematic VR Field Guide”, 2017, p.11). And the difference must be recognized by the user as well as communicated by the content creators. So in Jaunt Studios’ “The Cinematic VR Field Guide - A Guide to Best Practices for Shooting 360°” minimum VR requirements concerning 360 degree content are considered. They mentioned that they are aware of the fact that everyone would consider other essential requirements for a 360 degree VR video, but they focused in their choice on “maximum immersion and presence-the feeling of actually being there” (“The Cinematic VR Field Guide”, 2017, p.11). The first important aspect is that the image must be a full 360 degree equirectangular image where you can look around, up and down. Another important feature of 360 degree VR should be spatial 3D sound. Sound is a really important component of VR because it can lead the user through the experience and create a sense of presence in supporting the visual experience. The other requirement Jaunt proposes is that 360 degree video content must be viewed finally in an HMD to call it a form of VR. You need the viewing device to provide the immersive experience of VR such as spatial audio or stereoscopic viewing. Whether this is a Cardboard, mobile HMD or a room-scale HMD does not matter, concerning definition only in resolution and quality. Another requirement which is referred to is stereoscopic 3D whereas it is also pointed out that this is a contentious requirement. A lot of people capture film in a monoscopic way because it is cheaper and easier and also stitching is possible in a simpler way (cf. ibid. p. 11 f.). But “to truly get that sense of presence-of being present-that is the hallmark of VR you really need to shoot in stereoscopic 3D wherever possible” (ibid. p.11). Foundry describes Virtual Reality as “[...] the umbrella term for all immersive experiences, which could be created using purely real-world content, purely synthetic content or a hybrid of both.” (“VR/AR/MR, what's the difference?”, n.d). And concerning 360 degree content they state: “Our view is that 360° video, as an immersive experience, is one type of VR” (ibid.). So to say, 360 degree video can also be seen as one form of VR and like Jaunt Studios defined it VR applies for 360 degree videos with the proposed requirements.

In the following there is an approach to define different sub-categories of VR for the scope of this thesis. In *figure 33* there can be seen a modified and extended version of the tree diagram made by Jesse Damiani who tried to define a “Family Tree for Immersive media” (Damiani, 2016). There are the three major categories AR, MR and VR. VR has two major sub-categories which “differ on the means of production, playback method, realism, and amount of interactivity allowed” (“The Cinematic VR Field Guide”, 2017, p.7). On the one hand there is Responsive VR where you as user are able to interact with the environment and where the content is real-time rendered. This sub-category concerns VR Games on the one hand and Interactive VR Experiences, such as music videos or any other VR content which is interactive but not a game, on the other hand. The second sub-category is Cinematic VR which concerns 360 degree video content that is not interactive. The videos can be monoscopic or stereoscopic and divided into real-live content, three-dimensional pre-rendered content or a hybrid of both which can be seen as the ‘VFX’ form of VR.

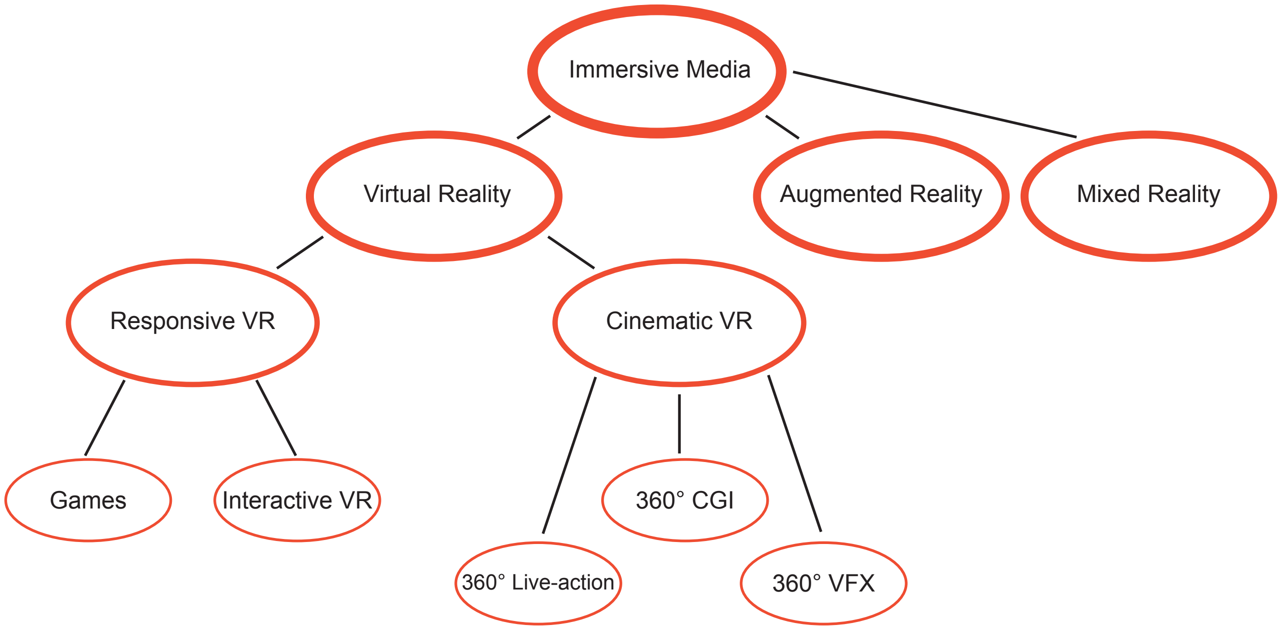


Figure 33: Family Tree for Immersive media. Adapted from Damiani, 2016.

The explained terminology and relations are only an approach to define VR and its sub-categories. They will be used in the explained way during the thesis, but they are not standardized terms. Just to emphasize this again at this point.

The most important features of Responsive VR are interactivity, as well as providing 6 DOF (translation AND rotation possible) and depth of field which allows you to move in a three-dimensional space. There are two major components such as VR Games and Interactive VR. VR games allow the user to interact and play in a virtual environment. Games are rendered in real-time and 6 DOF body-tracking is provided which makes them really interactive and the user has the possibility to lead through the experience. Interactive VR can also be seen as game-based VR because it uses similar features as games. But some of the experiences just do not fit in the term 'game' because, for instance, they lack the ability of rotation, but still provide interactivity as well as use the same real-time based workflow. So, that is why VR Games are separated to Interactive VR. In the Jaunt Studios' 'The Cinematic VR Field Guide' it is also stated that "Game engines are just as capable of making an interactive film or music video as they are a game and excel at creating worlds you can visit that are completely unlike real life" ("The Cinematic VR Field Guide", 2017, p.8). Interactive VR content can also provide so-called "invisible interactivity" (Damiani, 2016). Dave Dorsey, Creative Director of SilVRscreen Productions, describes that as a viewer you have the chance to follow the story which interests you the most. Through a gaze to a certain object or person in the video a reaction can be triggered to transport you into the story of that person or gives you a story with further information of the object (cf. ibid.). Also interactive overlays and interfaces, as well as audio or clip triggers, and gestures are possible features for 'Choose

Your Own Adventure' - stories (cf. “The Cinematic VR Field Guide”, 2017, p.9). Dorsey says: “For the first time, content can react to the viewer in a fully visceral and seamless way. The story doesn't need to stop in time for you to decide between two illuminated doors — the content already knows which you'd prefer based on where you have been looking” (Damiani, 2016). Whether this is enough interactivity to be considered VR is a controversy as well. Damiani claims: “There's disagreement over what constitutes the minimum amount of interactivity to be considered authentic VR” (Damiani, 2016). But concerning this issue the term Responsive VR as proposed of Jesse Damiani is a good umbrella term which works for all experiences that integrate interactivity in VR experiences in any way, invisible interactivity included.

The second sub-category of Virtual Reality is Cinematic VR. Cinematic VR is seen as non-interactive 360 degree video content throughout this thesis. Important is that it complies with the requirements which have been described above (360 degree equirectangular image, spatial sound, HMD, (stereoscopic image)). A 360 degree video is an equirectangular video that is morphed into sphere to playback on an HMD (cf. “360 might not be VR, but it's what VR needs”, 2016). So the user is inside the sphere while the video plays. “Unlike in game engines, however, you cannot move around the scene freely. Only if the camera is moved during filming do you move” (“The Cinematic VR Field Guide”, 2017, p.9). Video-based VR provides only three DOF, so only rotational movements. In comparison to Responsive VR, the film has a definite timeline and the viewer can watch it from different directions while playing. This content can either be live-action footage, pre-rendered 3D scenes or a mixed form of both. And the content can be divided into monoscopic (flat) and stereoscopic (3D) 360 degree video. The main differences by that is that monoscopic 360 degree video lacks depth of field. But stereoscopic live-action capturing can be a difficult task. Capturing, as well as stitching is a harder task with stereoscopy and therefore, a lot of content is monoscopic by now. But there is a lot of research in this field and Google Jump is one of the systems which provides capturing stereoscopic images and manages to stitch them in stereo, as already mentioned in the previous chapter. In all cases spatial sound should be available to increase the immersion and sense of presence in the scene.

360 degree content can be viewed in different ways. The first possibility is to watch it on PC where the mouse can be used to drag the view. In addition, there is only one image on the screen. The second option is for watching VR content on mobile phones. You can choose as viewer whether you want to slide a finger to change the view or you can turn around in 360 degrees with the phone in your hand. Here is also only one image displayed on the screen. And as explained in the beginning those two possibilities are not considered as VR, but are possible ways to watch the content on flat devices. Now coming to mobile HMDs where you attach your phones to, you can turn your body and head and change your POV. In this case, there are two separated images for each eye

provided to support stereopsis. The user will see these two images as one stereoscopic image and can feel more immersed than in the two options explained beforehand. Therefore, it can be considered as a form of VR. And room-scale VR headsets provide also stereoscopic images as well as 6 DoF and input devices to control the experience.

To sum up, you can say that due to the non-standardization of the term Virtual Reality, there is a lot of discussion and different opinions. Chris Milk CEO and Founder of Within mentions “if you feel presence in someplace you’re not, it qualifies as VR” (Situ, 2016). Throughout the thesis 360 degree immersive VR is considered as a special form of VR. It is a subcategory of VR which can also provide immersion, but in a lower level than other experiences. “I think as the technology improves we’ll start to see a blurring of the line between these things” (Cook, 2016), says Keith Miller, VFX supervisor. It could be that in future there will be another terminology for 360 degree content such as ‘immersive video’ or ‘3 DOF VR’ or something totally different. Important is that content creators as well as consumers know that there are different types of VR and that you have to have different expectations of the different forms. Jared Sandrews, creator and supervisor of visual effects tells in an interview with Ossic “My hope is that consumers will start to recognize the difference between monoscopic vs stereoscopic content, and 360 video vs the more powerful game engine content that provides the user with 6 degrees of freedom” (“Interview with Jared Sandrew - The future of Film and VR”, 2016).

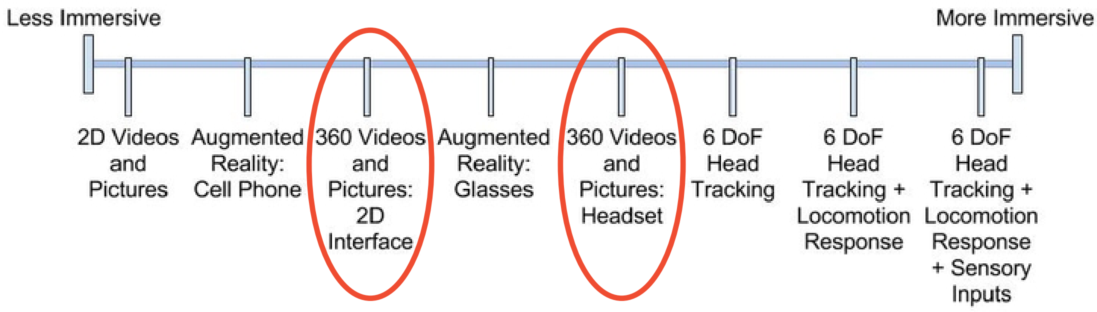


Figure 34: The Virtual Reality Spectrum.
Adapted from “360 might not be VR, but it’s what VR needs”, 2016.

3.2. VR AS TOOL

The first category which concerns the connection between VR and VFX focuses on the fact how VR as a tool can improve the VFX production process and give value to it. “VR becomes part of the production process, rather than the final experience” (Roettgers, 2016).

3.2.1 VIRTUAL PRODUCTION

The first application where VR can be applied as a tool is in Virtual Production. The VES describes Virtual Production as “a collaborative and interactive digital filmmaking process which begins with Virtual Design and digital asset development and continues in an interactive, nonlinear process throughout the production” (Okun, & Zwerman, 2015, p.444). In this context you can see Virtual Production as a virtual environment system in which you are able to collaborate and digitally exchange ideas at different stages of the production. This includes “world-building, previs, on-set visualization, virtual cinematography, character development and a digital asset pipeline that bridges all these practices” (ibid, p.444) as well as designing costumes, animation, light, camera work including framing and blocking, etc. Like this a lot of questions concerning creative work can be faced in earlier stages in production (cf. Dunlop, 2014, p. 304). And due to a highly flexible process, the technology can easily be transferred so that it fits exact the needs of the given production (cf. “The New Art of Virtual Moviemaking”, 2009 p.5).

One step of Virtual Production is Previs. Previs is the abbreviation for previsualization and could be described as “visual rough draft of a shot, sequence or show” (Okun, & Zwerman, 2015, p.45). Therefore, you can say, that it is a tool which should visualize the design and vision of the director in a production process. But previs can also be used to visualize complex issues concerning post-production and also for exploration and experimentation of possible techniques and ideas before processing. It is a common tool for communication and collaboration between different departments (cf. ibid, p.46).

So coming to Virtual Reality you can say that there are different approaches how VR as a tool can support Virtual Production. First of all, it could be a tool for creating previs. Joshua Ramsbotton of the University of Cape Town proposes a Virtual Reality Interface for Previsualization. In this paper there is only a prototype for a low-fidelity previs with low resolution models and no textures or rigging described. The user is able to navigate through the scene and to manipulate objects while being enabled to create a timeline with snapshots and key frames that can be inserted, deleted and edited. The user functions as camera in the scene and can make adjustments via head-movements and so the current positions are captured (cf. Ramsbottom, 2015). But in future it is thinkable that also high-fidelity previsualizations which include also other ways to interact in the scene and also include animation of objects and characters could be made via HMD in real-time. The advantage is that the user is set directly into the scene and can check on different perspectives of the characters.

Also for technical previs VR can be meaningful. Technical previs “incorporates and generates accurate camera, lighting, design, and scene layout information to help define production requirements” (Okun, & Zwerman, 2015, p.47). So VR can be a useful tool for environment and tech scouting. VR could provide a virtual environment where director, DOP and set designer could meet and discuss things such as resolution and framing as well as on shot direction and in best case can leave notes in the VE. That could be on the one hand useful for location scouting for upcoming shootings or on the other for checking out computer-generated environments. So for instance you could use apps such as ‘Google Earth VR’ to research and check out locations you might need for your movie before you really have been there or you can scan environments during a location scouting to build it in 3D and being able to walk through the location again and enable DOP and director to work before shooting on camera directions, actor positions, etc. Also, it could be a benefit for VFX productions with high CG environment content if these would also be walkable in VR. Same as with the scanned locations, responsible people could work collaboratively in this environment to check on improvements in the environment as well as on camera directions, spots where the action should take place and discussions about the set-design. This allows a really intensive way of pre-production and could lead to easier processes during the next stages of production and therefore to an enhancement of the whole production. “Virtual production and virtual reality are converging around the use of a game engine — technology that the gaming industry has been nurturing for many years. And now with head-mounted VR displays, it’s becoming an interesting way to do a kind of preproduction [location] scout and virtual production, so that you can feel the scale of the environments” (Giardina, 2016).

Another thinkable application of VR in the production process of a VFX production can be during On-Set Previsualization. On-set previs consists of real-time visualization on set where you can composite and synchronize two- or three-dimensional virtual elements with real-live footage for immediate visual feedback (cf. Okun, & Zwerman, 2015, p.47). So it is possible to capture an actor with, for example, Motion Capture (MoCap) and then replace it with virtual character on the screen to see how it fits in the scene. But besides that, there is no common tool at the moment that allows manipulating scene parameter such as the digital objects, animation, camera or lighting in the scene directly on set and integrates the changes in the film pipeline. The EU funded project ‘Dreamspace’ deals with the “research and development of tools that enable creative professionals to work collaboratively and combine live performances, video and computer generated imagery in real-time” (“About Project DREAMSPACE”, n.d.). The

Filmakademie Baden-Württemberg[7] is also one of the institutions which have been part of the Dreamspace project. They developed a Virtual Production Editing Tool (VPET) which should allow manipulating animation, set, light editing tasks in a real-time Virtual Production environment via an artist friendly and intuitive interface (cf. Spielmann, et al., 2016). What is special about this tool is that it can be integrated in every existing workflow because it constitutes a generic, real-time and open framework. The VPET can run on tablets as well as on HMDs. So all in all the VPETs suggest to offer a closer interrelation between real and virtual elements through direct manipulation by simplified hard and software interfaces like tablets and other VR and AR devices. The main goal which should be achieved is an on-set situation that should be comparable to the ways of early filmmaking where all creative decisions could be done directly on set (cf. ibid.). So to say, it should be a classical tool of Virtual Production where the people on set, mainly DOP and director are enabled to “observe, edit and quote virtual elements in a collaborative environment” (Helzle, & Spielmann, 2015, p.7). One of the features of the VPET is set editing which allows editing positions, scale and rotation of objects. The virtual camera is synchronized to the real camera so that the virtual objects can be seen from the ‘same’ camera and it is possible to change the virtual camera position in within the scene and the environment and the scene can be explored. Another possibility is to edit the light. Virtual lights can also be changed in position, scale, rotation and in light-specific properties, like cone-angle, intensity and light color. So you can manipulate lights in the virtual space as well as control the light panel for changes in the real scene. Also animation can be modified such as key frames of the animated objects as well as position and time issues can be identified and corrected. And the animation can be played on a synchronized global timeline (cf. Spielmann, et al., 2016).

So in this case the application of VR could be that you can configure the scene via an HMD directly on set and the configurations would be synced to the original film pipeline. For a previous prototype the team of the Filmakademie Baden-Württemberg used a gesture recognition controller (Magic Leap) with an HMD that was tracked via a MoCap system. It provided 6 DOF and allowed to execute the above described tool applications. But after a few tests they recognized that the gesture-based input devices lacked usability for users. Moreover, HMDs are also a problem with working on set because everyone who wears an HMD is isolated from the real world and unable to directly communicate issues on the real set. And mainly the whole work on set is based on team work and a lot of communication, so the switch between the real and the virtual set, under film production circumstances can be distracting and balking (cf. conversation with Kai Götz, 2017). At this point the team decided to use a user-friendly tablet which allows collaborative working and the possibility to display and transfer information to single persons and to gather their creative input (cf. Helzle, & Spielmann, 2015). So VR could have been

7 An international film school for film and media in Germany.

a solution to improve on-set previs, but it was figured out that tablets provide a better device in this case. Tablets are a better solution for multiple users because they remain in the real world. They function as a window to the virtual world which can improve your work in the real world. HMDs are an individual experience in within a VE.

For future improvements of the concept of the VPETs in Virtual Production, it could also be thought of the Microsoft HoloLens which could provide a better solution to build a bridge between real and virtual world. The HoloLens is a mixed reality device which allows you to see and interact with holograms through glasses in within your real environment. The headset is a medium performance PC and uses high-definition lenses as well as spatial sound to create an immersive and interactive holographic experience (cf. Roberts, 2016). For Virtual Production the HoloLens could be useful because you are still able to interact with the real world and environment while seeing holograms on top of that.

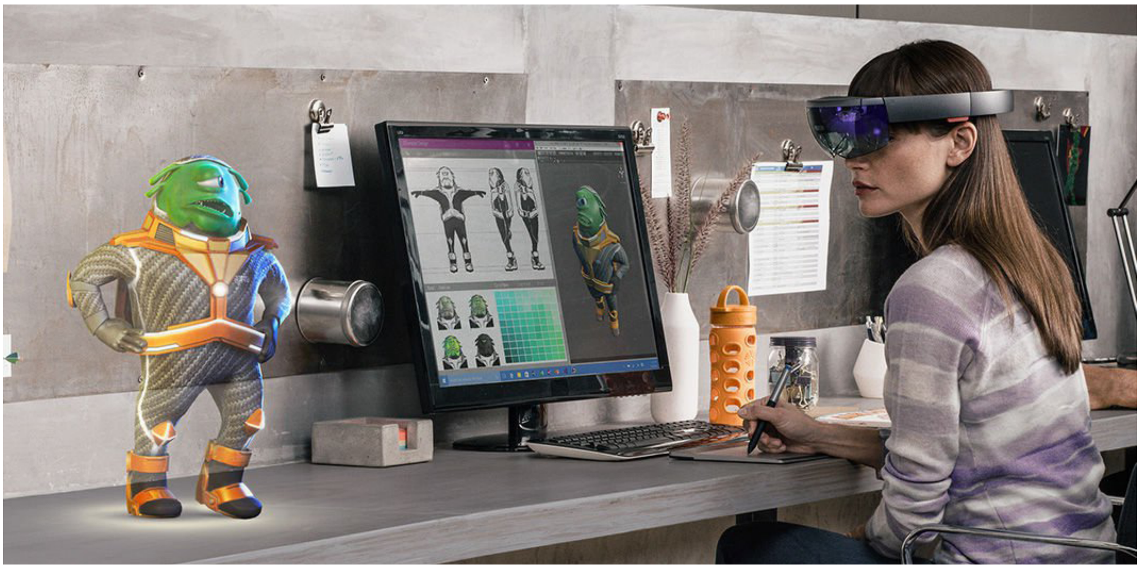


Figure 35: One possible application of the HoloLens.

Another case, which is a thinkable application of VR, is Virtual Cinematography. David Morin said in an interview that "since Avatar, virtual production capabilities have been expanding — he counted 17 such features currently in production — and he envisions a time when the virtual camera and the actual camera on a production merge into a single tool" (Giardina, 2016). In the latest Star Wars 'Rogue One: A Star Wars Story' also VR techniques got used to allow the director Gareth Edwards to frame up camera moves in CG shots. The technical team of Rogue One provided a tablet with Vive controller where it was possible to move around in within virtual space and find interesting framing and angles (cf. Singletary, 2017). So this is not considered as VR because you are not isolated from the real world, but the idea and techniques to VR are quite similar and, as described above, VR can also be used to walk through environments and capture camera positions and check out different angels and framings.

The last application of VR in previs, which should also be mentioned, is previs for 360 degree videos in general and specifically for 360 degree videos which contain Visual Effects. Previsualization is really important for VR videos because you need to plan everything exactly in detail. You need your actors to place at the right places and watch out that no one of the crew or any technique is visible on-set. So previs is on the one hand really important for the planning in pre-production, but also useful as overlay on live footage on set to check on how the VFX content fits to the live-footage. More to previs in VR 360 degree video with VFX content can be read in chapter '4.2.5 Previsualization'.

3.2.2 VR FOR VFX ACTORS

Besides Virtual Production, VR can also be a useful tool for movie actor rehearsal of VFX-enhanced scenes. As already mentioned, more and more movies have a greater amount of Visual Effects. Consequently, the more effects a movie contains, the more monochromatic green- or blue-screens surround the actor while playing. Sometimes it is really challenging for the actors to imagine the digital scenery around them as well as to interact with virtual elements such as digital characters or objects. They are not able to see virtual partners and so it is difficult to act responsive and keep up the impression of maintaining a consistent eye-line without real eye contact or interaction (cf. Bouville, et al., 2016). Ian McKellen, the actor of Gandalf in the 'Lord of the Rings' Trilogy and the 'Hobbit' sequel, also revealed that he became really frustrated from filming green screen scenes and therefore he burst into tears on the set of 'The Hobbit: An Unexpected Journey' (cf. Soghomonian, 2012). Another issue that can appear is extra costs if the filmed footage of the actor does not match with the CGI characters or environments. In this case, it can have huge impacts on the film production costs and often a reshoot is impossible to execute. One solution which can solve several issues is that the actors get the possibility to immerse themselves in the virtual scenery before the shooting (cf. Bouville, et al., 2016). Virtual Reality could support actors to get a better imagination about the environment where they act in green screen scenes. VR could provide virtual scenery which gives the actor an idea about what they should interact with and where they are situated in the scene. Also a virtual training, instead of the classical training, is possible where the actors can interact with a virtual partner and practice their play as well as rehearse their text. As the assets for virtual environments are built before shooting and mostly also used in a previs, they are also available to provide a virtual environment for the actor to rehearse in (cf. ibid.). All in all, VR could be used in this case to support actors to act in front of green screens via virtual trainings in the virtual scenery. What should be mentioned at this point is that VR could also be used for remote actor rehearsals. Due to that actors are always travelling and busy with shootings they cannot always be available at the same place at the same time. So via VR a rehearsal for a play can be provided with several actors from different places as well as with the director and then they can work in a virtual environment altogether (cf. Bouville, et al., 2016).

3.2.3 VR AS CONTENT CREATION, ARTIST AND REVIEW TOOL

Another possible application of VR can either be as review-, artist- or content creation tool. Already 1992 Butterworth et al. developed a tool named ‘3dm’. A three dimensional surface modeling program, which allowed the user to manipulate and understand the spatial relationships of models via HMD and lead to a more intuitive way of modeling (cf. Butterworth, et al., n.d.). The user was able to “build the virtual world from within the virtual world” (ibid.). 3dm’s purpose was to simplify the task of 3D modeling and provided head tracking as well as the possibility to “walk through the model space a few paces in any direction” (ibid.). All in all 3dm was especially efficient for “rapidly prototyping models” (ibid.). Nowadays there are Autodesk Maya plug-ins available to expand the 3D software to VR. Same as the 3dm they should provide an understanding of the relations in 3D space as well as create a feeling for the scale and proportion of the scene (cf. “VR-Plugin “Viewer”, 2016). One of these plug-ins is the VR Plug-In ‘Viewer” which supports the Oculus Rift and the HTC Vive. With this plug-in you are able to see from the view of a normal Maya stereo camera in your VR device. The HMD tracks rotation as well as translation to map your position on your Maya camera as live input. The artist is able to do modeling, texturing, lighting, shading and animation directly in VR (cf. ibid.). In the app description of the Autodesk App Store it is proposed that “You can use the software for presentations, previs, set design, animation, camera work including live stereoscopic camera adjustments” (ibid.). One really interesting feature of the ‘Viewer’ plug-in is that you can besides working on your model in VR also use the VR plug-in as approval or review tool where artists and CG supervisor could check better on the models. It is possible to import a model, mesh, and also lighting, shading and texturing in VR and the professional version even offers a mirror viewport which enables also other people to observe your actions on the monitor and interact at any time (cf. “VR-Plugin for Autodesk Maya”, n.d.). Another plug-in besides the Viewer’ plug-in is the ‘MAURI’ plug-in with similar features.

Figure 36: Working in Maya in a VR headset with the plug-in ‘MAURI’.

Another tool which is good for modeling, especially sculpting, is Oculus' in-house art creation tool Medium. Medium "focuses on manipulation of mass, rather than the production of brush strokes" (Lang, 2016). So the basic element in Medium is 'tools' which enables the artist to deform, cut, add and manipulate the digital mass in the scene via the Touch controllers. The volumetric geometry can be deformed by eight available tools that include clay (default tool, add and manipulates clay), paint (color your clay), swirl ("whirls your clay like a whisk" (ibid.)), cut (sculpt can be cut into pieces, moved and merged), inflate (extract or inject clay), flatten (get flat areas), smudge (clay gets smeared) and smooth (polishing of object) (cf. ibid.). Besides these tools there is a library where you can choose from over 300 stamps, which are predefined shapes such as letters, numbers or structural pieces. They consist of clay, which is also moldable and modifiable. It is also possible to create and save personalized stamps which can also consist of a combination of existing stamps. Stamps really are a good way of speeding up things concerning sculpting and building fast complex structures because it is easy to repeat a pattern and you don't have to draw everything (cf. ibid.). In *figure 37* you can see a good example where stamps have been used in a useful way. For the octopus' suction cups you just need to create one stamp and then you can spread it all over the tentacles in varying sizes. One special feature, which is really important for advanced creations which Medium offers, is layering. Like in Adobe Photoshop it is possible to work in the same scene, but in discrete groups that can be edited independently from one another. Another feature is that you can play audio while you are working in VR. There is a virtual speaker that plays any audio that is playing on your desktop and you are able to move the speaker around in virtual space so the feeling of a real 'working space' is generated. Despite all these good features, there are still some things which have to be figured out, such as the fact that you cannot blend colors yet and imported models need to be simple as well as animation is not supported yet (cf. Harris, 2017). You can export your creation "in a format which Oculus says can be used for 3D printing, or import into other 3D modeling tools or game engines" (Lang, 2016). Goro Fujita, illustrator and art director, is a good example for what potential Medium, as a modeling and sculpting tool, has. He already did a lot of artworks in Medium and shows how Medium can be used as a professional VR creation tool. "In a way it's even more intuitive than sculpting with real clay. Being able to grab your model,

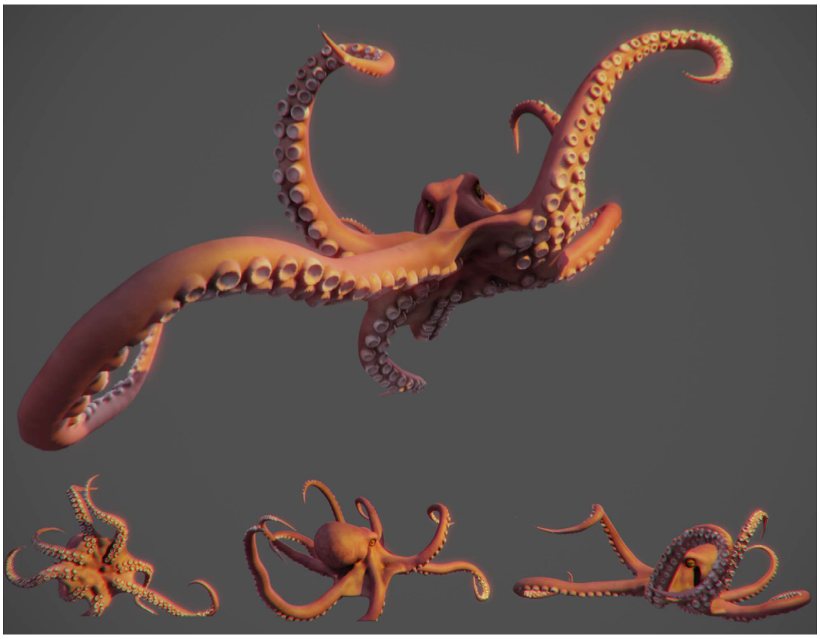


Figure 37: Medium sculpture 'Octopus' from John Paul Sommer.

scale it to the size you like for adding details all the way to spray painting it by grabbing the model with one hand and spraying with the other is just something you weren't able to do before. It's a truly magical experience and removes almost all the technical barriers that traditional software packages have and it lets you focus on what you want to create" (Nafarette, 2016). In the following *figure 40* you can see an artwork created in Medium by Goro Fujita. In *figure 41*there is a 3D-printed version of an artwork, also by Goro Fujita.

Figure 38: Working in Medium, no 1.

Figure 39: Working in Medium, no 2.

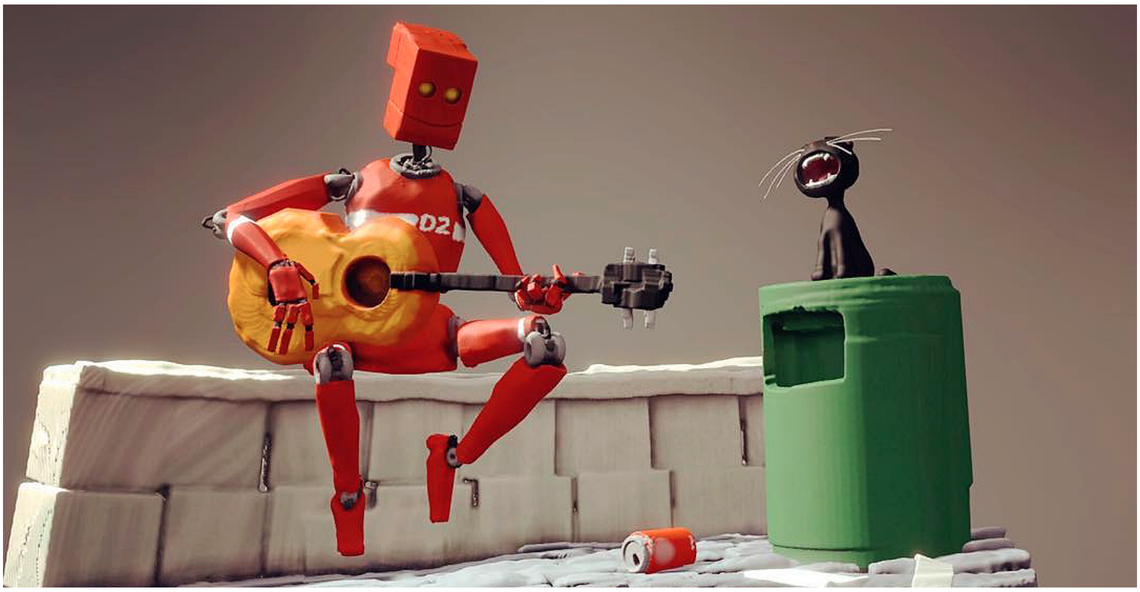


Figure 40: Artwork by Goro Fujita.

Figure 41: 3D-printed sculpture of Medium. Artwork by Goro Fujita.

Besides the plug-ins for Maya and the Oculus' Medium tool, also other applications are developing that provide prototypes of modeling tools in VR. One example is the program Massit, a simple massing and rendering tool which can be used for fast mass spatial concepts (cf. Winkler, n.d.). It allows really fast and basic modeling and can be used for visualizations and concepts. *Figure 42* shows some examples.

Figure 42: Examples created with the program Massit.

Concepts, that can be useful for a pitch or concepts of characters or environments, can also be made by a few other tools which allow the user to create them in an easy, fast and intuitive way. One of these tools is Google Tilt Brush which is predestinated for the HTC Vive. Tilt Brush enables people to draw inside a three-dimensional space in VR by using different brushes and colors to create an artwork where they are able to walk around in and to scale it like they want (cf. Harris, 2017). In *figure 43* and *44* you can see artworks created in Tilt Brush which could have been used as concept of a creature and an environment. The artworks can be saved and shared as room-scale piece or as animated GIF (cf. Harris, 2017). Furthermore, Tilt Brush could also function as set-design tool. Set designer could create virtual versions of their ideas and the directors would be able to walk through these and make notes on that (cf. Harris, 2016).

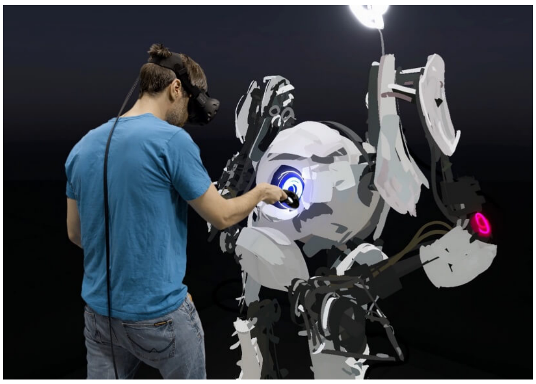


Figure 43: Tilt Brush artwork no 1.

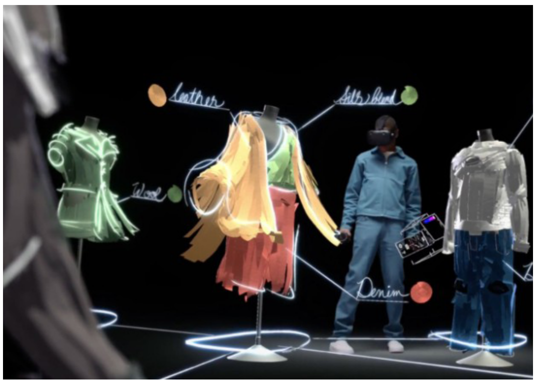


Figure 44: Tilt Brush artwork no 2.

Another tool which is quite similar to Google Tilt Brush is the tool Quill by Oculus Story Studio which works for the Oculus Rift. The main difference is that Quill offers the ability to draw in space and time, which means it can also be used as a production tool to tell stories. So it can also provide new form of virtually drawn art videos such as the illustration film ‘Dear Angelica’ by director Saschka Unseld and art director Wesley Allsbrook. Every scene of the movie was hand drawn and the “film screened on Sundance Festival as the first animated experience created entirely in VR” (Harris, 2017). Screenshots of ‘Dear Angelica can be seen in *figure 45* and *46*.

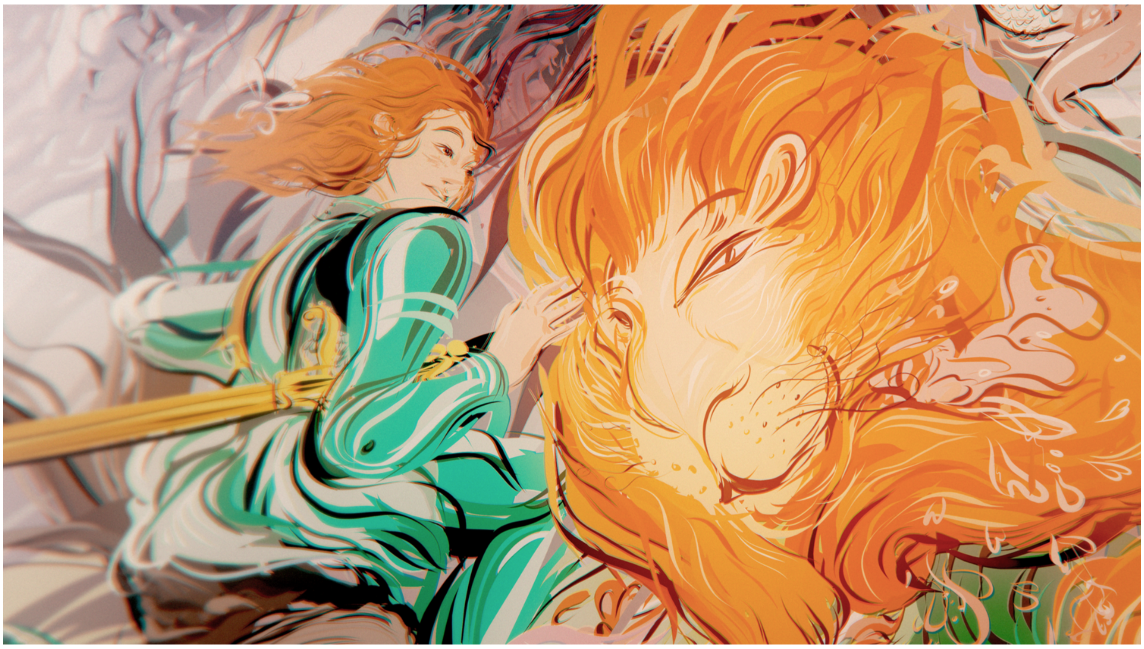


Figure 45: Screenshot from the VR film ‘Dear Angelica’ (2017), no 1.

Figure 46: Screenshot from the VR film ‘Dear Angelica’ (2017), no 2.

Quill also allows the user to manipulate reference images as well as sound files. In addition to drawn or sketched VR narratives, Quill is also useful for character and art development as well as for conception, like already mentioned (cf. Harris, 2017). Besides different brush shapes and strokes, Quill "offers the ability to work in watercolour, pencil, oil painting and comic format among others" (ibid.). The artworks can be exported as 360 photos or videos, high-resolution screenshots and also as animated GIFs. One special feature that Quill also has, is the fact that you can work with scale and it is possible to create really detailed paintings where you can zoom in and zoom out (cf. ibid.). In *figure 47* you can see an example for such an artwork, again by Goro Fujita.

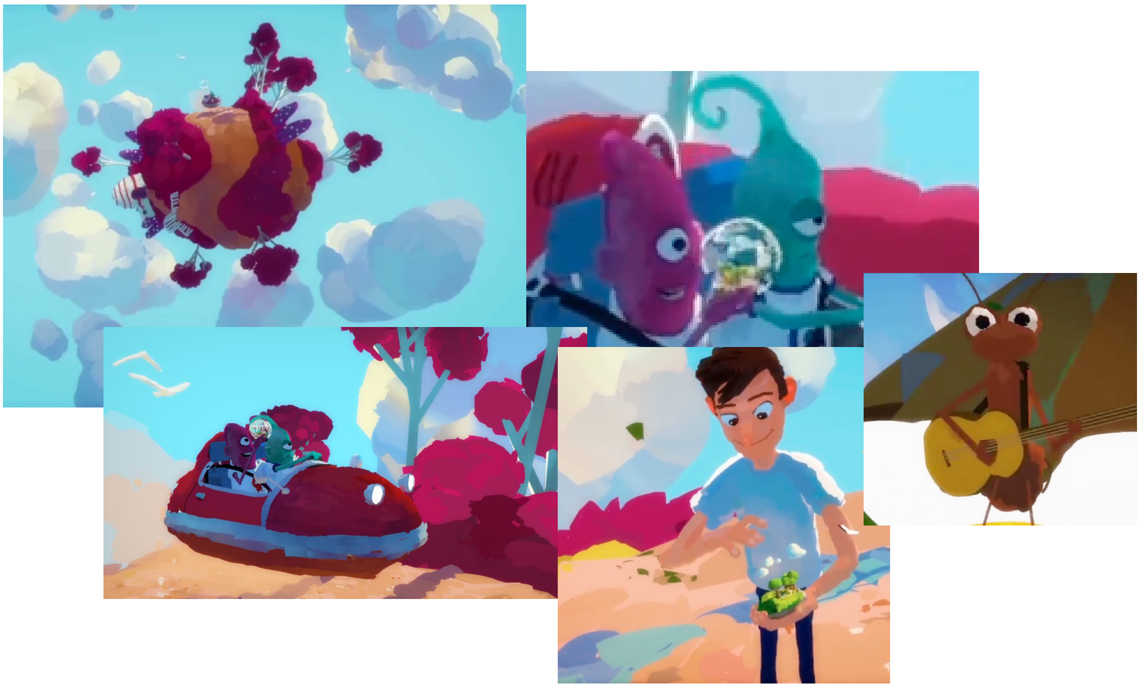


Figure 47: Collage of different parts of the 'zoom image' in Quill by Goro Fujita.

In February 2017 Foundry previewed also new VR toolset for their program Modo. This new in-house technology codenamed 'Project Mayhem' was shown during a Modo Live event which took place at Gnomon, School of Visual Effects, Games and Animation in Los Angeles (cf. Thacker, 2017). With the set of VR tools, user are able to navigate through Virtual Reality scenes directly in Modo and they can 'teleport' from one point to another, such as it is the case in many VR games. The goal of VR is to step in a virtual world and use tools in a natural way like we are used to (cf. Gnomon, 2017, 01:48:00). Modo enables users to manipulate foreground objects as well as to preview models very easily. Greg Brown, Foundry creative specialist said at the live event that he can imagine that VR could play a practical role concerning asset review because you can check better on the assets. "When you're inside this environment, every flaw, every error [in an asset] becomes apparent" (Thacker, 2017). The VR editing tool allows to check on wireframes, textures and also on scale (cf. Gnomon, 2017, 01:57:00). Another feature

Modo offers is that you can move around a character and check on animation in VR as well. You can step through an animation via on-screen controls in both directions (cf. Thacker, 2017). Therefore, Modo can also be used as animation review tool. "[Working with the technology] has changed my perspective on how content should be created. In my opinion, virtual reality is an essential part of content creation at this point" (Thacker, 2017), Greg Brown said. Additionally, the display quality and the viewport rendering got optimized due to the improvements which had been made for the VR toolset. There is no release date of the technology yet, but it shows that more and more tools for VR got developed.

Other imaginable ideas for VR tools could be using VR for asset libraries or as a tool for Grooming. Grooming tools are important for the creation of hair, fur or feathers. Normally, it works with drawing curves on a mesh. So, a possible application for VR could be that users are able to draw these curves directly on the mesh in a virtual environment (cf. conversation with Georg Wieland, 2017).

3.2.4. VR AS COMMUNICATION TOOL

VR can also be a possible tool for communication. Due to greater understanding of things by viewing them as 3D visualizations, meetings in VR can be useful especially to interact and communicate with people in other countries (cf. Houck, et al., n.d.). VR can overcome geographical boundaries and also be a tool for teleconferences, which can be useful for VFX companies with different locations all over the world. The founding director of Stanford University's Virtual Human Interaction Lab, Jeremy Bailenson, says that "business calls using virtual-reality technology can offer many benefits over videoconferencing" (Zakrzewski, 2016). One huge benefit of communicating in VR is that also nonverbal communication, such as gestures, is enabled. Mr. Romo, chief executive of AltspaceVR Inc, explains that "There are all these nonverbal cues we have physically that we don't have in [most] communication technologies except for VR" (ibid.). Fine movements like finger gestures, as well as facial expressions, are not able to be captured yet. Therefore, the reflection of emotions is still a difficult task in VR. But these issues are in development and some companies try to overcome the problem with emotions in VR via integrating transitional technologies, such as emojis (cf. ibid.). But even if emotions are not possible like in the real world, VR offers another way of interacting and collaborating in comparison to common communication technologies. There can be a white board

Figure 48: How a conference in VR could look like.

in the virtual environment where users are able to point to or manipulate drawings or texts. There can be virtual objects which can be discussed. So, immersive collaboration can help teams to work closer together and develop ideas in one virtual environment. “In the context of office meetings you now have a whole virtual environment where you can co-create and interact” (ibid.) said Mr. Harlick, head of the Bank of Ireland Worklab, who experimented with VR as teleconferencing tool. AltspaceVR is the first Social-VR community and provides integration in Slack since April 2016 (cf. Lang, 2016). The main focus is to connect family and friends and through sending links you can invite user to join a specific AltspaceVR room with them in which they can meet and communicate in real-time. For colleagues and professional contacts the slack integration was provided, so that it is easier to share a link to an AltspaceVR room for a meeting (cf. ibid.). AltspaceVR is “one of the most fully developed platforms” (Robertson, 2016) for social interaction in virtual space, according to the technology news website The Verge.Besides the presented tools in this chapter there are a lot of other tools which are in development right now or also can be used for certain tasks in production pipelines. And there probably will be an increasing development for further tools in the next few years.

3.3. VFX TECHNIQUES FOR INTERACTIVE VR

Before going on with the next two fields where VR and VFX correlate, there is another question which has to be faced. What is VFX? And what is ‘VFX for VR’? The definition of what VFX is and what techniques include VFX, raises the same problem as with the definition of what really VR is. The definition of ‘The VES Handbook of Visual Effects’ is “any imagery created, altered or enhanced for a film, or other moving media, that cannot be accomplished during live action shooting, and further expanded to include virtual production – the process of capturing live images and compositing them or reinterpreting them into a scene in real-time” (Okun, & Zwerman, 2015, p.1). But techniques of VFX, such as for example CGI tasks or 3D scanning, converge with full-animation movies and also games. There are differences like that in a game the viewer can influence the camera and move in space (translation) and story, interactions must be programmed, as well as the duration, format types or distribution platforms are different. But concerning the making, there are some commonalities such as asset building (even if the LOD is another at games creation because of the real-time rendering) and animation (even if for games animations are quite short to trigger every single small move depending on the player’s demand) (cf. Dunlop, 2014, p.5 ff.). A main difference is that VFX, in comparison to games, is not rendered in real-time and has no constraints, except deadlines or budget, concerning render time. But as real-time engines get better and better this cannot be a difference that can be considered in future. That is why there will be following subdivision in scope of the thesis: Responsive VR follows a game-based workflow and will therefore not be considered as ‘VFX for VR’. The Cinematic VR workflow, however, is very much alike the common VFX workflow. Responsive VR requires a seceded department with another workflow in within a VFX company. Even if VFX artist can also contribute to the asset building of Responsive VR, the assets still need to be converted and integrated into another workflow. For the creation of 360 degree VFX content this is not applicable and such an experience can also develop in a VFX company without VR department (cf. conversation with Georg Wieland/ Patrick Heinen, 2017). The VFX workflow needs to be customized at a few points for the needs of VR, but as a whole, it is pretty much the same with some exceptions. “While VFX artists can still use their skill set and experience, they have to adapt them to different techniques that fit a very new medium” (“VR Post Production - Kilograph”, 2016). So to say, 360 degree immersive video VR content can be seen as the medium where the common VFX workflow fits best. Of course, you need to be aware of that every project is always unique and has special requirements that need to be faced. As Responsive VR is not directly considered ‘VFX for VR’ the next sub-section deals with VFX tools and techniques that can also work to create interactive VR experiences.

3.3.1 INTERACTIVE VR BASICS

First of all, a short description of the main differences in a Responsive VR production workflow is given. As already mentioned in the section above, Responsive VR has some techniques that are also used in VFX in common, but it demands another workflow. This workflow has quite the same approaches that are known from common game development. One main difference is already in the pre-production stage and concerns the concept development. Even if 360 degree videos demand another way of storytelling and concept, there are quite a few differences to Interactive VR. In both cases, the user decides how the content plays out. But in 360 degree videos users are just able to choose view angles where they want to look at, they cannot directly interact with objects in the scene (except if it applies to ‘Invisible Interactivity’ like explained in the section above; though the only way to interact there is through gaze directions, meaning no ‘real’ interaction. Therefore it will not be considered as Interactive VR and is more a sub-form of 360 degree videos) or decide where to ‘walk’ next. Moreover, Interactive VR consists of a nonlinear story and is not predestined like 360 degree videos which tell an immersive story and you cannot influence the length or action of it. You just watch it in different angles. So, in Interactive VR or VR Games you have a “progression structure” (cf. Dunlop, 2014, p.30). You need to think in advance about dependencies, for example in a flow diagram to visualize what action of the user could result in what reaction and how an action can influence the experience (cf. conversation with Tina Vest, 2017). You have to make sure that the ‘gameplay’ or the following actions, the experiencing of the story remains engaging for the viewer. Furthermore, you need to do a priority- and milestone-list to check what features you really need for the experience and which features would be nice to have if there is still enough time in production and the rest worked out well. Defining milestones is also important because it gives the producers possibilities to check on the progression of the experience. In comparison to a VFX movie or also 360 degree VFX movie, a producer is always able to check on results and progression because it is possible to see direct results after changes in the DCC tools. Responsive VR whereas consists of a large amount of programming where it can be possible that you have no visual feedback for days (cf. conversation with Tina Vest, 2017). Consequently, games are normally divided into ‘vertical slices’ and ‘horizontal slices’ (cf. Dunlop, 2014, p.30). “Each of these is intended to lay foundation for a different aspect of the production work” (ibid. p.30). The horizontal slice (final-quality gameplay) is responsible for the ‘White Box Level’ which means that the logic and the function of the gameplay are tested just without textured assets and animation, really similar to a blocking in a VFX movie, but with the possibility to get a feeling of how the gameplay will turn out. Vertical slices (final quality assets) define small sections of the play and work as milestones like described above (cf. ibid. p.31). The goal is to “provide confidence in the development process itself” (ibid. p.31), “convince management of the project’s viability” (ibid. p.31) and it is also a “gateway to production” (ibid. p. 31) because it allows the producer to track the preproduction and see results. In Responsive VR the same approaches can be taken because it has similar workflows and requirements. Additionally, the code of the game must be sufficiently documented because if one programmer gets sick or leaves the production, other people need to follow the code he or she used for the experience (cf. conversation with Tina Vest, 2017).

The first main application that is used in VFX as well as in Responsive VR, are 3D computer graphics programs. They usually work in three-dimensional space where objects can be edited and there is a manipulation of space and time possible (cf. Okun, & Zwerman, 2015, p.866). Programs like Maya, Houdini, Modo, Mari, 3ds MAX, MudBox, ZBrush, etc. can all be used for the purpose of 3D content creation for interactive VR experiences or games. “The CG medium is helping the two [VFX & Games] share their creative crews” (ibid. p.858). And VR as new medium can be incorporated in that. “3D CG programs, as well as 2D paint programs, are generally termed digital content creation (DCC) tools” (ibid. p. 866). Mainly the programs for asset- or environment building are suitable for both workflows, except that the artists of Responsive VR have to be more careful concerning polycount and need to approach animation in a different way. In comparison to VFX, where animators animate a movement over longer time, it is important that for Responsive VR the animation is divided into short movements. Like this, movements compound together depending on the player’s demand. Concerning assets, a VFX company could even benefit of having a separate Responsive VR department with another workflow because assets that are used for a VFX movie could also be used to realize a promotion VR experience according to that movie. “By being in both visual effects and VR, effects studios can also re-use and re-purpose assets they make for films into other mediums, and have the same artists contributing to the process" (Failes, 2016). But one must be aware that the assets for the interactive workflow have other needs so that they can be implemented into a game engine. The work with the Level of Detail is quite similar, meaning, that depending on the camera distance, a high or low-poly mesh of an asset is used. If an asset is farther away from the camera, the asset switches to a low-poly version to minimize memory and rendering costs (cf. Dunlop, 2014, p. 77). Even if the work with the LOD in Responsive VR and 360 degree VFX videos is quite similar in general, a much lower polycount is needed for the interactive experience assets and the polycount itself is more critical in VR games and interactive VR experiences. Due to the focus of DCC tools is not on "efficient organization and playback of interactive [...] experiences" (Okun, & Zwerman, 2015, p.867) and they are not suitable to deal with logic and manipulation of data, an alternative is needed that is able to define and modify logic systems to create an interactive experience through "writing computer code, scripts, manipulating visual logic controls, or a broad mix of these" (ibid. p.866). So, game engines are needed at this point. They receive the content via export from the DCC tools, such as for example an obj. After that, the obj. can be exported and modified so that it is appropriate for the engine (cf. ibid. p. 867). "Because a game is interactive and has to respond immediately to the player's action, the frames need to be rendered in real time" (ibid. p.851). And by meaning real time, everything which renders faster than 30 frames per second is considered (cf. ibid. p.851). But, with real time there come constraints, such as for example, like mentioned before, the requirements of low poly count meshes. For VFX movies in comparison, a render-time of 10 to 20 hours per frame might be possible, which implies that there is enough time to finalize a shot. The handling of data in real time is harder. Another difference is that changes in the VFX workflow are hard to do, because of the long render times and steps you need to redo. In real-time, changes can be made more easily because there is no need for, for example, 20 hours rendering, and whatever they want to change does not influence render time. But changes also affect the entire experiences and can lead to bugs or other problems that endanger the interactive experience. There is another huge difference which is the 'finalling phase' of interactive experiences. This step requires a lot of debugging and user test experiences to provide a fully working interactive experience in the end. In a 360 degree video, that follows a VFX workflow, the movie is finished if all shots are rendered in the expectant way and do work properly in a HMD.

Coming to other techniques that are commonly used in VFX and could also be used in the Responsive VR workflow. 3D capture software such as Photogrammetry or LiDAR scanning are common applications that are used in the VFX workflow to generate a three-dimensional environment and to receive seamless VFX and CG integration. But these techniques are also suitable for games and the interactive VR workflow. There are also other possibilities to create assets or environments, such as surveying or image-based modelling, but in the following, photogrammetry and LiDAR are presented.

3.3.2 PHOTOGRAMMETRY

Photogrammetry is a method which is used in different fields, for example architectures, engineering, manufacturing, geology as well as in VFX and games development for creating real looking assets or environments (cf. “Types of Virtual Reality Capture Methods That Allow You To Replicate The Real World”, n.d.). For photogrammetry several photographs shot from different angles and positions of an existing environment or object must be made and with this information a three-dimensional reconstruction of the captured environment or object can be generated. Through at least taking two pictures from different positions, “so-called “lines of sight” can be developed from each camera to [corresponding] points on the object” (ibid.) or environment. Due to photogrammetry is based on triangulation, these ‘lines of sights’ are mathematically intersected to create points in three-dimensional space (cf. ibid.). So, that is basically what photogrammetry software does. It “reconstructs [...] the geometry by analyzing and comparing perspective lines and shading information in several related photographs of the same environment” (Kerlow, 2009). So the software looks for common pixels in within the images and tries to figure out which relationship they have to each other in space through calculating all the camera positions (cf. Edwards, 2015).

One example for such a VR experience which has been created from photogrammetry is a scene of the VR company RealityVirtual from New-Zealand. It shows a realistic looking virtual scene with geological formations on the coastline of Aotearoa and was generated in Unreal Engine 4 (cf. Higgings, 2016). In the *figure 49*, a screenshot of this experience is provided. RealityVirtual says on their photogrammetry VR projects “Photogrammetry for game development is awesome and we see it as a great tool to aid in immersive story-telling” (“The making of ‘Photogrammetry to VR’ teaser”, 2016). And Cargo Cult mentions in his article about ‘Photogrammetry in VR’ “Being virtually transported to another, real location - and then walking around in it - still feels like something from the far future. Some of the most immersive VR experiences I’ve had so far have involved scenes captured in this manner [photogrammetry]” (Cult, 2015). In *figure 50* and *51,* two other screenshots of photogrammetry capture can be seen. These are from another company, which is called Realities. Moreover, *figure 52* and *53* show another example of photogrammetry.

Figure 49: Screenshot from the VR experience of the Aotearoa coast by RealityVirtual.

Figure 50: Screenshot from photogrammtery-captures environment by Realities, no 1.

Figure 51: Screenshot from photogrammtery-captures environment by Realities, no 2.

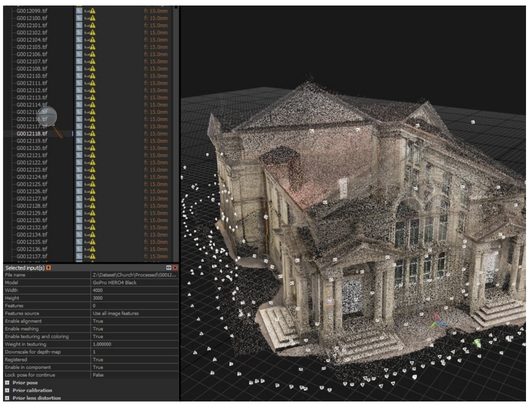


Figure 52: 3D scene creation with photogrammetry, no 1.

Figure 53: 3D scene creation with photogrammetry, no 2.

3.3.3 LIDAR

Besides Photogrammetry LiDAR scanning is a common technology which is used to capture 3D environments. LiDAR means "Light Detection and Ranging" and is a laser scanning technology which is able to measure distances and capture 3D data. LiDAR is used in VFX for on-set surveying, matchmoving, and previsualization as well as for environment and asset creation or set-extensions. "LiDAR represents one of the most powerful tools available for rapid, accurate 3D modeling of large-scale sets, locations, and props" (Okun, & Zwerman, 2015, p.153). Therefore, it is also a suitable method for Responsive VR because it is a central component of setting up appropriate models and data to visualize. "LIDAR range scans can be used to quickly create accurate 3D models for virtual reality and as a basis to visualize sets of photographs, videos, and virtual objects in a cohesive environment" (Bui et al., 2016). Due to the speed of light is known, LiDAR scanners can measure how long it takes for light from a laser pulse emitter back to a receiver. While doing this, the LiDAR scanner calculates from the direction in which the ray was emitted and the distance, the final x, y, z location of the hit point in space. Through scanning these reflected points, extremely accurate 3D "point clouds", consisting of across millions of points, are created. These point clouds can be stitched with specialized software and then LiDAR data can be delivered in different formats, which can be used as basis for further editing or integrating in different workspaces (cf. Okun, & Zwerman, 2015, p.153). LiDAR scans are commonly done as multiple scans from different positions to "cover any occlusion that may occur from fixed point scans" (ibid. p.154). LiDAR is often used for aerial scanning of cities or landscapes. But it really depends on how huge or dense the scanning environment is. A large area can be scanned with less effort and from possibly only one position, in comparison to a city where skyscrapers and other obstructions are given and so the LiDAR system needs more positions to capture this environment (ibid. p.151 f.).

One example, where LiDAR got used to create an interactive VR experience, is the 'St Margaret's Church Experience'. The VR experience was shown in the scope of the Vespertine[8] cultural event in York, England, and was a coproduction between the AOC Archaeology Group and National Centre for Early Music (NCEM). The experience was a colorful immersive digital journey with sound. The experience was suitable for mobile as well as for HMDs. "Artist and technologist Annabeth Robinson and musician Jez Wells have translated these scans into an installation and VR experience allowing us to experience the building in a whole new way" (Hutchinson, 2016), said Delma Tomlin, director of the NCEM. In *figure 54* and *55* an impression of this artwork can be gained.

8 A free and monthly festival with different performances and events hosted in the most beautiful places of York, England.

Figure 54: Screenshot of the 'St Margaret's Church VR Experience', no. 1.

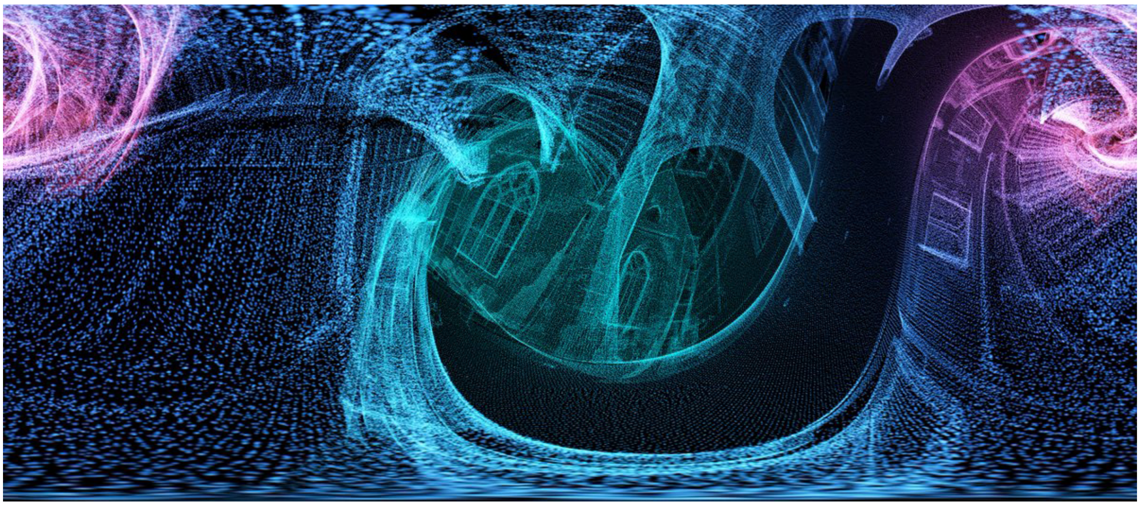


Figure 55: Screenshot of the 'St Margaret's Church VR Experience', no. 2.

Moreover, there is an app available which allows the user to navigate inside of 3D point clouds. It is called "LiDAR VR Viewer" and is an Android application. It can be used with simple HMDs such as the Google Cardboard and the navigation into the data is performed by a Bluetooth controller. Point cloud ASCII files as well as mesh surface Wavefront .obj files are supported (cf. Morel, 2015). An example of the app interface is seen in *figure 56*.

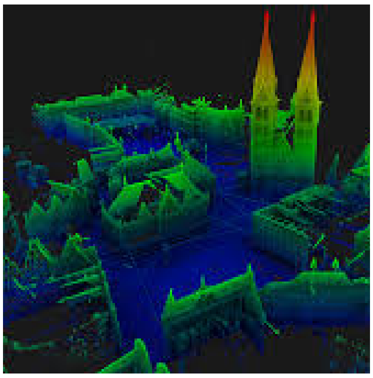


Figure 56: Example image of the 'LiDAR VR Viewer' App.

In the next chapter there will be a closer look on how VFX techniques can be suitable for 360 degree VR video.

3.4 VFX TECHNIQUES FOR 360 DEGREE VIDEO

In comparison to Responsive VR, 360 degree video fits quite well to the common VFX workflow and most of the techniques. “Some of the hardest things to solve in VR are things that VFX artists have been trying to solve for years, including stitching panoramas and 360 degree video, compositing, HDR lighting, dealing with stereo and making digital assets” (“VR Is A Key Component Of VFX’s Future”, 2016). So, “VFX artists can still use their skillset and experience but need to adapt different techniques that fit that new medium” (“VR Post Production – Kilograph”, 2016).

In general you can say that 360 degree VFX video is still more complex because of several reasons, such as a considerable higher amount of data, as well as other requirements of shooting and postproduction and different content and experiences. One main difference to common VFX productions is that there is no framing in VR. Normally, you can hide things in VFX through framing or cutting to another frame, but in VR everything is visible. “You can’t be just concerned with what’s happening in one particular area or one particular direction. You have to be looking at what’s happening behind you, what’s happening off to your left, off to your right and you’re animating and working with an entire world rather than this little tiny slice of action” (Cook, 2016). So to say, a carefully crafted composition is not possible anymore and you have to create a world around the action and also consider parts of the image where no actual attention is. “In a regular VFX shot for a film, you have a carefully crafted composition and camera move. So that’s completely gone now” (ibid.). Moreover, VR is a really viewer-centric medium. You have to think about what the viewer is doing, seeing, feeling and how he might act and react to things. Also, a 360 degree VFX workflow is more time consuming than the common VFX workflow. On the one hand there is a greater amount of data which needs to be handled, transferred, edited and saved, on the other hand the material needs to be stitched before reviewing and editing. And reviewing the material demands also a higher expenditure of time because it needs to be reviewed in all directions for several times. Post-production is also a challenge because of working with an equirectangular image. There is another capture resolution at the poles than it is at the center of a latlong image and dealing with a spherical environment can be confusing. Motion blur for instance, cannot just be put like on a normal image. It is not possible to just streak the blur from left to right because it has to follow the curve of the latlong (cf. “HELP – fxguide”, 2015). Another thing is that the whole VR - VFX workflow pushes the limits of hardware and software (cf. Tanchum, 2016). VFX artists might be a little spoiled concerning their common software because they are used to find a tool for any need, but right now publicly available VR tools are still rare and need to be developed. So it requires a lot of experimentation and searching for solutions to get a 360 degree VFX workflow to work. And also real-time processing is still a challenge that needs to be solved. Assets can also be reused in the 360 degree video workflow such as in Responsive VR. “Since VFX studios are often behind the asset-builds in major films or TV shows, it makes sense that those same assets (and studios) might also be used in VR experiences for promotion” (Failes, 2016). And if on the begin of a production it is already settled that there will be a VR experience besides the main movie, the VFX companies can prepare on that, also in considering the asset building. Another difference is that in comparison to VFX, which is an established field with already existing workflows, practice as well as a market, VR is still in its beginning and has no funding or distribution channel.

As a whole, you can say that the VFX - VR workflow differs from the common VFX workflow, but the skillset of artists is quite similar and they are keen on finding solutions. In addition, they have a feeling for scale. 3D artists have already worked in three dimensional spaces and also dealt with 360 HDR images for light setups for instance.“Our compositors, lighters, and trackers have excellent spatial awareness” (Failes, 2016), mentions Aruna Inversion VR supervisor of the VFX house Digital Domain. “They understand the limitations of 360 video, and how to build such worlds effectively within our software packages” (ibid.). John Fragomeni, President of Mirada states to that subject, “We immediately realized that 360 degree video uses the same workflow and tools as high dynamic range (HDR) imagery; obviously it’s not that simple but the foundational issues are the same” (ibid.). Like already explained in section ‘3.1 Controversy About the Terminology’, 360 degree video with VFX can therefore be considered as ‘VFX for VR’. To gain better understanding of how a 360 degree workflow works, there will be a detailed look on the workflow in chapter four and in chapter five. Such a workflow will also be explained on the basis of the case study of the Google Spotlight story film ‘HELP’.

3.5 GETTING CLOSER

“All of this leads to a completely new form of media. A blank canvas with which we’ve only just begun to realize what’s possible. The “killer app” in VR will be some combination of cinema, gaming, and interactive theatre. Right now we’re only in the dress rehearsal and anything is possible. Even just five years from now VR content will look nothing like it does today” (“The Cinematic VR Field Guide”, 2017, p.9). Lightfield as well as other new technologies could bring VR and VFX closer together in future. “As new camera systems and acquisition technologies are developed eventually you will be able to move around filmed scenes as well.” (ibid. p.9).

3.5.1 LIGHTFIELD TECHNOLOGY

One of these techniques, which promise that you could possibly walk in a 360 degree video, is the lightfield technology. Lightfield captures how light interacts in an environment, for example, how it bounces off objects or in what angle photons arrive and are presented in the eye (cf. Wren, 2016). Lightfield can be one future representation of VR filmmaking and could also lead to a merge between games, VR and VFX. With Lightfield, live-action VR with composite CG elements could be possible as well. Lightfield can be described in a simple way as “all the light that passes through an area or volume” (“Types of Virtual Reality Capture Methods That Allow You To Replicate The Real World”, n.d.). Unlike focusing light through a lens onto a camera sensor, a lightfield camera consists of hundreds of micro-lenses that capture light rays from every cogitable direction (cf. “The Cinematic VR Field Guide”, 2017, p.16). It does not enable to walk in VR movies yet, but the captured footage allows shifting parallax in horizontal as well as vertical way and provides “true depth and perspective regardless of your viewing angle” (“Types of Virtual Reality Capture Methods That Allow You To Replicate The Real World”, n.d.). You are also able to refocus the image, generate depth maps, to view stereoscopic 3D and to pull mattes without a green-screen (cf. “The Cinematic VR Field Guide”, 2017, p.17). One of the first cameras in this area on the market was a still camera called ‘Lytro Illum’. Meanwhile, Lytro released two other cameras for the professional video market which are the ‘Lytro Cinema’ and ‘Lytro Immerge’. The ‘Lytro Immerge’ is a lightfield camera especially for VR. Instead of one micro lenses array that lightfield still cameras offer, video based light field cameras use a few camera modules which are arranged in a sphere or grid configuration (cf. ibid. p. 17 f.). “With that captured Light Field data, the Lytro Immerge system mathematically reconstructs a spherical Light Field Volume, which is roughly the same physical dimension as the camera.” (“Types of Virtual Reality Capture Methods That Allow You To Replicate The Real World”, n.d.). After the processing procedure the “multiple video streams can be packed into a compressed light field format that enables you to move around the scene as the video plays-albeit limitedly“ (“The Cinematic VR Field Guide”, 2017, p.16). There is still limitation in movement due to the width of grid or the diameter of the sphere but shifting parallax is still possible which minimizes motion sickness (cf. “The Cinematic VR Field Guide”, 2017, p.17 f.). Thinking of spheres and grids of lightfield cameras getting bigger and capturing a wider field of environment, one could theoretically move farther than nowadays possible. But there is still the problem with a huge amount of visual data that needs to be processed by a large array of computers that must be capable of capturing and processing this data. If you think of live-action VR, there is also the problem that this mass of data must be playable in a real-time environment with an appropriate framerate (cf. Wren, 2016). Moreover, downloading, streaming and working with light field streams is a real challenge concerning today’s bandwidths (cf. “The Cinematic VR Field Guide”, 2017, p.18). Lightfield is not only interesting in the future because of possible live-action VR and easier post processing of merging 3D elements with real-live footage in VR space, but also a huge advantage for VFX industry. Like mentioned above, no green-screen will be needed anymore because mattes can be taken out of the depth data of the lightfield. Lytro CEO Jason Rosenthal says in this connection “We’re capturing all the depth and the 3D geometry of the real world, so compositing computer-generated objects into that with the right depth and the right shading and shadows and lighting, that all becomes much easier than it’s ever been before” (Moynihan, 2015). There will be no need for motion capture anymore because integration of real life people will be possible. Lytro produced the 45 second long test film ‘Moon’ which is “the first ever piece of six degrees of freedom 360 live-action content” (O’Kane, 2016). In *figure 57*, there is a screenshot of ‘Moon’ and a woman trying the experience in an HMD.

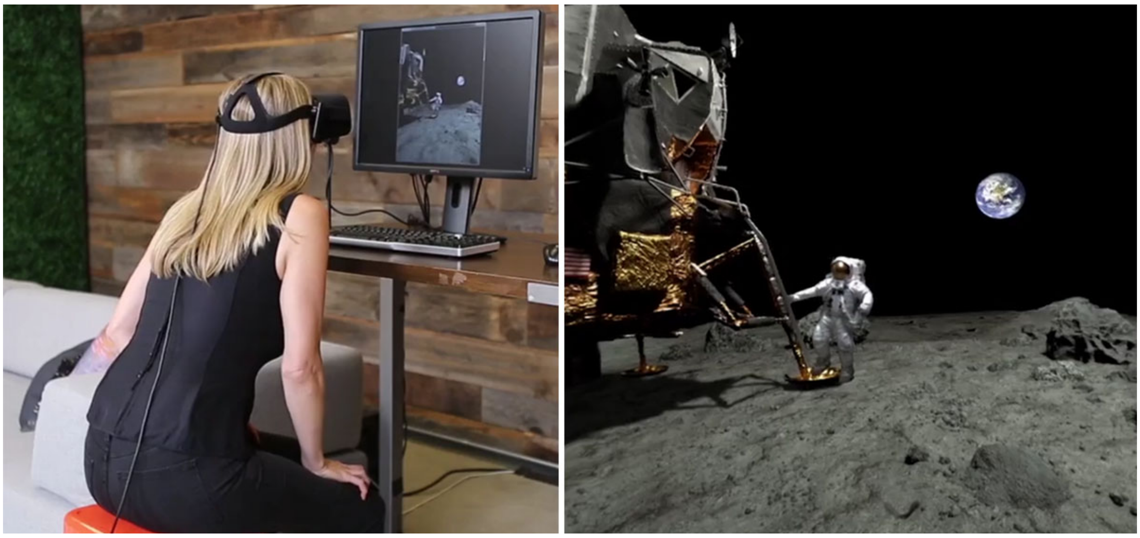


Figure 57: Lytro experience ‘Moon’.

Figure 58: Lytro Immerge camera.

It shows what can be possible with lightfield technology. In an interview with The Verge, Lytro CEO Jason Rosenthal showed first a raw version of the footage that has been directly captured on set. There were a lot of 'depth artifacts' especially around the moving parts of the scene. But for a live preview on set, the footage would be good enough to use (cf. O'Kane, 2016). Compared to that, the post-processed cleaned version of 'Moon' was "composited with computer-generated elements and another 3D shot of the accompanying sound stage" (ibid.). By leaning forward, the perspective and the surface reflections on the objects in the scene, such as the astronaut or lunar lander, change (cf. Rubin, 2016). So in the clip, Lytro succeeds in bringing all different elements, such as the computer-generated lunar lander and moon surface, as well as a real actor in costume and the additional Hollywood soundstage together to a seamlessness VR experience that shows what this technology is capable of (cf. O'Kane, 2016). Milliron, Lytro's vice president of engineering, says that videogame engines provide high-immersion, but instead low-reality, and for 360 degree videos it is just the other way round because they can create photorealism but lack movement and interactivity (cf. Rubin, 2016). So Lytro tries to find a balance between that and "seeks to produce work that's both high-realism and high-immersion" (ibid.).

3.5.2 VOLUMETRIC CAPTURING

There are also other companies besides Lytro working on lightfield solutions, such as for example the company Uncorporeal which does "holographic reality capture" ("Uncorporeal", n.d.), also based on lightfield technology. And also concerning volumetric 3D capture, more and more people are trying to find solutions to real-time capture objects, humans or environments and to create dynamic volumetric videos where it is possible to walk around in. Companies, such as for instance Microsoft, 8i or HypeVR, work also on capturing solutions for VR. Microsoft and 8i approach an outside-in capturing method instead of inside-out methodology in their camera capture technologies. They film with an array of cameras that face to the inside of the scene; so to say, they surround the scene with cameras (cf. "The Cinematic VR Field Guide", 2017, p.18). For its HoloLens, Microsoft has created a video based photogrammetry technology which is able to create holographic videos. Through an array of cameras around a green-screen stage, video from different angles is captured and then advanced photogrammetry techniques are used to generate computer-generated 3D meshes with mapped textures (cf. ibid. p.18). "Their technology uses advanced mesh tessellation, smoothed mesh reduction, and compression to create scenes that you can actually walk around in VR or AR" (ibid. p.18).

8i uses common high-definition cameras that record video from the outside to the inside to capture people from several viewpoints. 8i specialized on human holograms where you can walk around, after processing all the data to a real-time fully volumetric 3D human (cf. “8i”, n.d.). After that, you are able to bring your hologram, for example in a computer generated or live-action Virtual Reality environment. “360 video can be very beautiful, but it’s also an adaptation of technology from the past. What 8i is doing is absolutely, fundamentally innovative” (Terdiman, 2015), says Nonny de la Pena, cofounder of the Emblematic Group, a company creating VR experiences. In *figure 59*, an example of such a hologram integrated in an environment is given.

Figure 59: 8i hologram of woman with child.

The approach of HypeVR is a little different and consists of a combination of depth mapping LiDAR and high-quality video capture. The rig remains static in the scene and later the texture data of the video and the depth data of the LiDAR are combined in a 60 ‘frames’ per second volumetric scene. In comparison to photogrammetry in this approach also fast moving objects, such as for instance water moving, can be captured. The methods of photogrammetric capture are not fast enough in this case. In general HypeVR creates every ‘frame’ new real-time rendered 3D models which are played back one after another. That allows the viewer to move around and creates a sharp and immersive experience (cf. Lang, 2017). Further information can be found on their website which is provided in the appendix.

A huge advance which all volumetric video capture methods provide, is the possibility to merge live-action screen captures seamlessly with CG or live-action environments. That would also provide a great advantage for VFX and VR techniques. But everything is still in it the beginning and there are several issues to solve until lightfield or volumetric video captures will be common technologies that are adapted in the VFX, VR and games industry or also in other fields. “I don’t think anybody knows how VR is going to be shot in a year or two” (Rubin, 2016), said Milliron in an interview with Wired.

3.5.3 REAL-TIME TECHNOLOGY

“Virtual Reality (VR), Video, and Video games are converging” (Mollet, et al., 2015). And working with real-time in game engines can also be a subject that could bring VFX, VR and games closer together. “…there is no question that each field is influencing the other” (Okun, & Zwerman, 2015, p.193). “It’s an exciting time for VR and visual effects, and we seem to building toward an eventual merging of disciplines” (Edwards, 2015), said Hubert Krzysztofik, Director of Interactive Technology of Pixomondo. VFX becomes more interactive through VR as medium, and games “are becoming more cinematic, and many of the tools, artists, and programmers in either field are converging because they both use similar computer graphic techniques” (Okun, & Zwerman, 2015, p.858). So you can say, that the workflows of the different areas get closer. Krzysztofik mentions, “Game engines already have a nascent presence in the VFX industry and are increasingly being used in pre-visualisation and look development” (Edwards, 2015). Real-time is already used in some cases for VFX workflows, for example in on-set visualizations. “Real-time visual effects require a real-time camera tracking process to instantly calculate and record all physical camera motion and lens information: xyz motion through space, pan, tilt, and roll, plus zoom and focus” (Okun, & Zwerman, 2015, p.194 f.). On the basis of this data it is possible to recreate the camera in within the computer-generated environment and match it and move it upon the real world image (cf. ibid. p.194 f.). Real-time Visual Effects will become an important tool such as storyboard or previsualization that helps to understand the shot and what will be seen in it (cf. ibid. p.200). “As such, real-time effects and tracking systems may become a standard tool to expand options and give more freedom to the creative process and imagination” (ibid. p.200).

However, besides the use of real-time in VFX for previewing on-set to improve the overall production process, there might also be other conceivable applications for it in the future. As graphics of render engines get better and better, it is also thinkable that VFX movies will be rendered in real-time one day. A few good approaches will be introduced in the following.

The first project previewed at GDC 2016 and won the 2016 SIGGRAPH award for Best Real-Time Graphics and Interactivity and was called ‘Hellblade: Senua’s Sacrifice - From Previs to Final in Five Minutes: A Breakthrough in Live Performance Capture” (cf. Cowley, 2016). It was a cooperation between Epic Games, Ninja Theory, Cubic Motion and 3Lateral with further support from House of Moves, IKinema; Technoprops and NVIDIA for the live performance at SIGGRAPH. As a whole, the presentation showed that a scene from Ninja Theory’s upcoming game ‘Hellblade: Senua’s Sacrifice’ can be shot, edited and rendered in real-time in front of a live audience (cf. Cowley, 2016). In comparison to common film and game previsualizations the presentation showed that the techniques that have been used for ‘Hellblade’ “empower creatives to capture, edit, playback, and export to offline 3D applications and output to video at any resolution" (ibid.). Moreover, it is possible to publish the content to VR platforms. The characters facial expressions were captured previously, in order to adapt these on the CG character in the live-performance. In addition, the CG character as well as the environment must be created in advance but "every nuance of the digital character's facial expressions, lighting, visual effects and sets are visible in real time to final render quality" (ibid.). In the performance at SIGGRAPH the actress even played two characters. In the first performance, the actress acted as a ghostly version of the main character Senua. The camera takes in this case the part of the real Senua to guarantee the counter shot. After that, the actress played the second character, the 'real' Senua, which could be seen simultaneously with the before captured performance of the ghostly version of herself. "The third version is an edited version of the action, where a virtual camera can 'film' the action" (Seymour, 2016). There, you can see both characters from a wide view on the blocked scene. This could be received through the Sequencer tool of Unreal Engine 4 that allows to live-remix viewer of real-time rendered assets (cf. ibid.). "You can use it to mix emotional aspects of a performance as easily as a video editor cuts filmed clips, since everything is live and real-time of course." (ibid.). So to say, everything what is captured and rendered goes directly as 3D data into Unreal Engine 4's Sequencer tool. 'Real-time cinematography', as its creators call this technology, is definitely a really good tool to use in Virtual Production and for previsualization, but as this improves it is also possible that it will be used for real-time live action films combined with CG elements or people replaced with CG characters (cf. Cowley, 2016). Like Tameem Antoniades, Chief Creative Director of Ninja Theory said in the presentation at GDC 2016 "previs is not the end goal" (GDC 2016, 2016, 00:08:20 ff.) and "with the quality of graphics, lighting, characterization we've got here, I don't see why you can't create entire productions, virtually with virtual humans, right now" (ibid. 00:08:26 ff.). He even mentions that facing a digital human in VR can make the whole performance even more believable. He said, "When you're actual in Virtual Reality facing a digital human and you're looking into the eyes of this character it really puts you there, you believe that that person is real" (ibid. 00:08:50 ff.). Moreover, he stated, "Our end goal is to find ways to create fully interactive 3D experiences for future games and virtual reality experiences that feature incredible, immersive worlds and believable characters. This amazing collaboration between our teams had brought the dream a huge step forward to everyone's benefit" (Cowly, 2016). And also other voices reacted to this project, like for example CEO of Ninja Theory Nina Kristensen said, "We're looking to work with partners that are interested in using this new technique for their projects, whether this be in games, movies, VR or live performance. We see this new technology as a game changer and are proud to be pushing the boundaries of possibility in this space" (ibid.). So, 'Hellblade: Senua's Sacrifice' was chosen as one of the examples because it shows how real-time can be a benefit and

Figure 60: Ghostly-self of Senua and Senua.

Figure 61: Ghostly-self of Senua.

Figure 62: Live-capturing at SIGGRAPH '16.

Figure 63: Facial expressions of the actress change on the character in real-time on screen.

gateway between VFX, VR and game technology. More detailed information can be read in the fxguide article 'EPIC win: previs to final in five minutes' provided in the footnotes and the performance can be viewed in the provided link, as well in the appendix. In *figure 60, 61, 62* and *63* you can see screenshots from the performances at GDC 2016 and SIGGRAPH 2016.

As Unity is actually not known for its good graphical capabilities, in comparison to Unreal Engine for instance, they created a quite compelling graphical result with their showcase real-time rendered film 'Adam' which introduces their cinematic Sequencer tool. 'Adam' was built with beta versions of Unity 5.4 and showcases the graphical quality which is achievable with Unity in 2016. There were quite a few new developed custom tools and features to provide a good graphical result. So, there was also volumetric fog, transparency shaders and motion blur features developed which should be also available after the production for free (cf. "Unity – Adam", 2016). 'Adam' was also presented at GDC in 2016 as a short version to preview the film. So 'Adam' is also an indication for games getting more cinematic and yearning to improve their graphical capabilities.

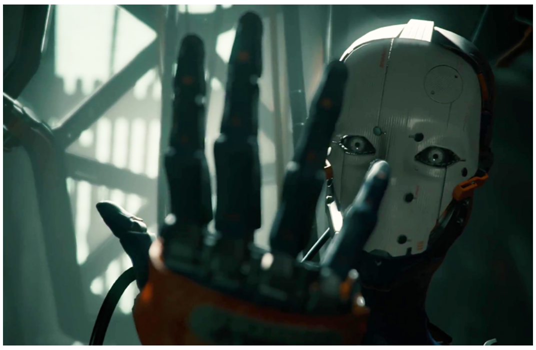


Figure 64: Screenshot of ‘Adam’, no.1.

Figure 65: Screenshot of ‘Adam’, no.2.

Figure 66: Screenshot of ‘Adam’, no.3.

Figure 67: Screenshot of ‘Adam’, no.4.

More information and the link to the movie are provided in the appendix. In the following you can see some screenshots of ‘Adam’ (cf. *figure 64-67*).

You can say that the game engines prepare for new requirements and try more and more to provide capabilities for cinematic real-time rendering. There are still not much traditional VFX finishing applications involved. There is no compositing apart from some post effects and the realism is still a challenge. But everything is improving and in development (cf. conversation with Patrick Heinen).

Real-time is definitely a future technology also for CG and VFX. Veselin Efremov, team member of Unity’s ‘Adam’ demo team, says “You mean CG animation facilities and vfx studios? Yes, definitely, realtime technology is the way to go. […] It allows for fast iteration, which enables creative people to spend much more time exploring and trying out ideas, instead of waiting for hours for a single frame to render” (Efremov, & Nechevski, 2016). And real-time engines can also be important for Virtual Reality experiences. Hannes Ricklefs, Head of Software of MPC Film explains, “For fully immersive experiences, it needs the quality of VFX at the speed of a game engine” (Edwards, 2016). So for that, VFX and VR need to come closer together and they definitely will if technology improves. Hubert Krzysztofik says to that issue, “I’m looking forward to seeing how VR continues to develop and improve, and how it can be beneficially integrated into the VFX industry and beyond” (ibid.).

4

WORKFLOW

360° VIDEO
VR AND VFX

“IT WILL BE THE WILD WEST AGAIN!”

– Michael Abrash, CTO of Oculus (“VIRTUAL REALITY – What’s necessary to make it real?”, n.d.)

Figure 68: Stitching lines of an image from the film ‘HELP’ (2015).

Due to determining that 360 degree video with VFX can be seen as ‘VFX for VR’ because of the similar workflow in chapter three, this chapter concerns the workflow and the different stages of a 360 degree VFX production. As already mentioned in the section 3.4 ‘VFX techniques for 360 degree videos’, VFX studios are also predestined to create VR content and you can apply the classical VFX workflow to the 360 degree VR workflow and extent it. “Despite its challenges, however, producing VR is not as different from traditional VFX as people imagine. There are some key differences, but none that are too extreme” (Coulombe, 2016). This chapter tries to get through the basics of a 360 degree production workflow with all important stages, such as before starting, pre-production, production, post-production, audio and distribution. The field of VR is still in progress and everyone is still learning. “As a completely new medium, it's about diving in and learning. Best practices are still being defined and challenged every day” (Robinson, 2016). “You will need to be humble enough to learn over again; you need to be prepared to try new methods“ (ibid.). So this workflow is assembled from different approaches and opinions and should give an overview about the most common aspects a 360 degree VFX video production consists of.

4.1 BEFORE STARTING

Before starting with a project some questions have to be considered. For example, if VR is the right medium for the purposes of the project and what value VR as medium gives to it. Another question is: What is the wished achievement with using VR? Joergen Geerds, CEO and creative director of KonceptVR affirms,”… one of the primary things that we verify before we even begin to engage in a 360 video production is the question: Does it even make sense? So would it be more practical as a standard ‘flat’ production that can be better handled with traditional media?” (Pinson, 2016). So, does your project offer the viewer a new experience with new aspects which are not possible in another medium? Such as placing the viewer in places or into actions where he or she cannot take place otherwise? Is VR the better medium to address emotion if the sense of presence is reached? And is that what you want to show interesting enough and engages the viewer to look around and explore the possibilities 360 degree video as a medium offers? And does VR enhance the intention of your project? (cf. “Lesson: Introduction to 360-degree video and virtual reality”, n.d.). Kirk Shintani, Head of 3D of a52 states, "[VR experiences are] much more enjoyable if you can find a project that truly takes advantage of the immersive qualities of VR. Push past what others have done, and find new, creative ways of using this cool technology" (Robinson, 2017).

So another big question is, as VR is an audience-based medium, “Does this add value to the audience? Is it memorable, or is it more advertising noise and clutter?” (Robinson, 2016). For that, also the form of VR must be decided. What kind of experience should it be? Live-action, pre-rendered in a synthetic medium, such as animation, or should it be an interactive, gaming experience or an app? These kinds of things must be considered before starting. Also thinking about what is possible with the medium, what possible boundaries of technology exist and which areas would require research before starting is necessary. Considering the 360 degree workflow with VFX it is crucial to think about what can be possible in 360 degree and what not. For instance, real-time rendering is still critical, but improves from time to time, so it must be considered for the purpose of the project if it is possible to work with and what challenges will come with it.

Being sure about a few things, before taking action and starting the pre-production of the project will contribute to a better planning and will also help to better evaluate the outcome of the production (cf. Ergürel, 2016). Phillip Moses, head of VR content developer Rascali opined, “I think it’s important to start with a very important question of “Why VR?” And once you believe you have a compelling answer to that question, then you need to start thinking about how to use VR in your story” (Altman, 2016).

4.2 PRE-PRODUCTION

In this phase, the development of the story as well as research, scheduling, tech decisions and defining specs play an important role besides resource planning, budget allocation and team building. In this context Kirk Shintani advises, “First, planning ahead is critical. For pre-rendered output, know what you're getting into as far as duration of the piece, frame rate, output resolution and estimated render times. It's also important to give yourself time to test the different compressions for delivery” (Robinson, 2016). Audra Coulombe, Marketing Manager of The Molecule mentions that it is a good idea to bring different departments, such as the camera team and the post production facility at the begin of production together to let them talk about the best ways to solve shooting and the stitching of the cameras in post (cf. Coulombe, 2016). As a whole, it is an approach to the project from different points of view in pre-production. There is the technological aspect, as well as the User Experience (UX) and User Interface (UI) strategy and the creative part of creating a story around the medium VR. For RnD one must be aware of the available technologies and what needs the project has. Moreover, there should be specs defined before starting with shooting and post-production such as thinking about which hardware integration and on which platform you want to distribute your project. And of course, the script and story must be defined and visualized in a storyboard or even better in a previs where you can already check on your ideas in the medium VR via HMD. “To create a great VR project, some of the most important decisions need to be made in pre-production and production. This principle is very similar to any project that requires visual effects — if you plan and shoot it well, post-production won’t be as laborious and expensive” (Coulombe, 2016).

4.2.1 SCRIPT | STORY

“You can’t cut. You can’t fade. You can’t move the camera. You can’t pull focus“ (Chocano, 2014). VR goes beyond traditional filmmaking rules and techniques and creators must be aware of all directions in their story. So a script for VR must contain not only a story but also a world where the story takes place and it needs trigger moments to get the attention of the viewer to the right direction. Due to scriptwriting and storytelling for VR could fill one paper alone, there are only some of the main aspects mentioned in the following.

“We’re storytellers, and we tend to think big. That's what’s great about working in visual effects and working with software like Maya; it allows us to think outside the box and push the boundaries of storytelling. We don't just take what we've got and transport it to VR; we ask if we can do something extra to take it further. What we bring is the opportunity to expand the narrative and tell stories in spaces that haven’t been told before... It's a very exciting place to be right now" (Robinson, 2017) notifies Andy Rowan-Robinson, Creative Director and Head of CG of the Framestore VR Studio. So, what is the best way to tell a story in VR? “The core of VR is experience and presence” (Gajsek, 2016). So the main goal of the creators is that the viewer feels ‘there’ in their experience and that the viewers can also stay focused for a few minutes and enjoy the moment of being and exploring another environment than the real world (cf. Chocano, 2014). “…it’s not just about the content itself. It’s also about creating the right conditions for the viewer to feel a part of it,” (ibid.) said Lajeunesse from the studio Felix and Paul. “… in VR , we feel an urge to slow down, to land and really explore the moment” (ibid.).

VR storytelling can be compared to being in a video game (cf. Gajsek, 2016). You also have to ask you the question which role the audience plays in the story. What kind of role do the viewers get? Are they stationery or are they moving? Are they in normal height or maybe on another height level to induce some emotions? How do you lead their attention towards the action? And how do you let the viewers interact with the story? How do they get involved? Or do they serve as observer? Things such as these mentioned must be considered when writing a script for VR. “It’s important to remember that the stories don’t change, but the way we tell them in VR will change” (Gajsek, 2016). But in VR you need to use different methods to express your intentions and the messages you want to transport with your story. “It’s a creative dance, a push and pull of image, performance (or blocking in film terms), and pace” (“VR Filmed Production Workflow Development”, 2015).

“If only one thing happens in VR at any given time, as is the case in film, the world quickly starts to feel empty and strangely fake” (Unseld, 2015). We live in a three dimensional world where rarely only one action is taking place around us. As VR offers a virtual world, the storytelling should also deliver three-dimensionality. “Even though time for the viewer unfolds in a linear fashion, the discovery of the story might not. This realization, of course, had big implications on staging and timing” (ibid.).

“Stories and storytelling should be as three dimensional as the space around us” (ibid.). Oculus found a name for this way of describing what happens around us and called it ‘spatial story density’ (cf. Wray, 2016). That means, to reach a sense of presence no more singular storytelling is needed, but as in real life also several things are going on around us and not only one single action, VR needs three-dimensionality. And the density of the story elements should fill these spaces (cf. ibid.). “The density of information that is conveyed in film versus VR is clearly different” (Unseld, 2015). In film you have one main storyline and one focus. In VR the focus is on three different action compartments. One focus is on the main action (1), also known as ‘Cone of Focus’ or ‘Cone of Experience’. That is where the primary action takes place and what happens right in front of the user. The secondary actions (2) are what happen on the sides, in the peripheral of the viewer and the tertiary focus (3) is on the back. “You want to keep important things within the primary action panel as much as possible” (Wray, 2016). Joergen Geerds contributes, “They [the viewers] always need to know where the main experience is, and we direct their attention so that they will not miss it” (Pinson, 2016).

Therefore it is useful to think about the story as a series of ‘moments’ instead of actions.

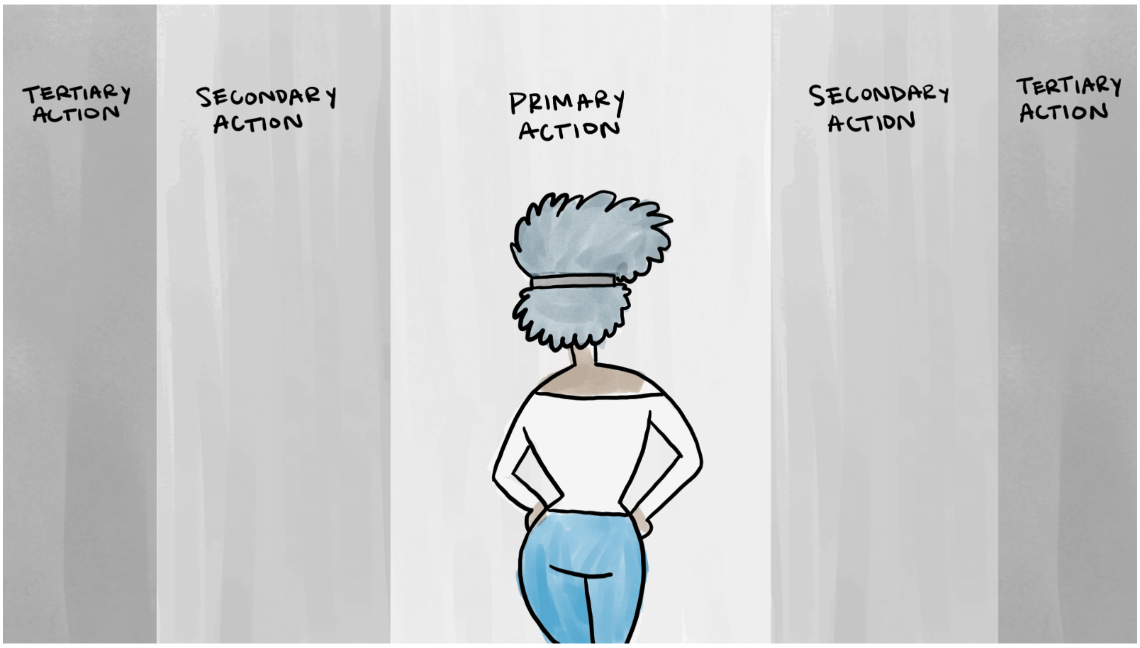


Figure 69: Visualization of primary, secondary and tertiary action.

Figure 70: Visualization of Cone of Focus and peripherals.

With this thought the audience will have enough time to understand each moment and you will need to find the right pacing to lead them through your story. (cf. Unseld, 2015). One has to be aware of that the story does not become too rushed and the viewers maybe have struggles to follow the actions. So screen writing for VR can be compared to building a world in where actions take place and then connect this world and actions to your story.

As already mentioned, you need to be aware of pacing in VR. It is important to acclimatize the user to the medium VR and give him break points where he can let down and just experience the environment (cf. „How to Build Better Stories in VR", 2016). So you should allow the user time to get orientated in the new location. "Consider how long it will take to explore each shot, then move on to the next place" („Lesson: Shooting in 360-degrees", n.d.). In addition, there are many people out there who have not tried VR yet. "VR is still new, there is no right way to watch these shows yet. The audience needs to be taught how to watch each project – from within the project" (Robinson, 2016). And that is controlled amongst others by the UI. But also pacing plays a huge role in adapting the user into the story and the new medium. But on the other hand, one has also to watch out that the story does not become too boring if the pacing takes too long. "Don't let the pacing be too slow or drag on for too long – experiences are immersive to an extent, but can quickly become boring" (Robinson, 2016).

Normally, first-time users will automatically look straight in one direction like how they are used to from watching flat screens (cf. Gajsek, 2016). Lucien Harriot of the company Mechanism Digital suggests, "Keep your story – the majority of the subject matter – in front of the user. Even though they're able to look around in 360, they typically don't" (Robinson, 2016). And Aruna Inversin from Digital Domain talks about a paper from 1996 that Disney presented at Siggraph about Storytelling in VR where some tests show that "In many scenarios, people in HMDs do not turn their heads very much" (Inversin, 2016).

In *figure 71* you can see histograms that show the pitch- and yaw-angle of an HMD and it definitely shows that most of the time was spent at one angle-area (cf. Pausch, et al., 1996).

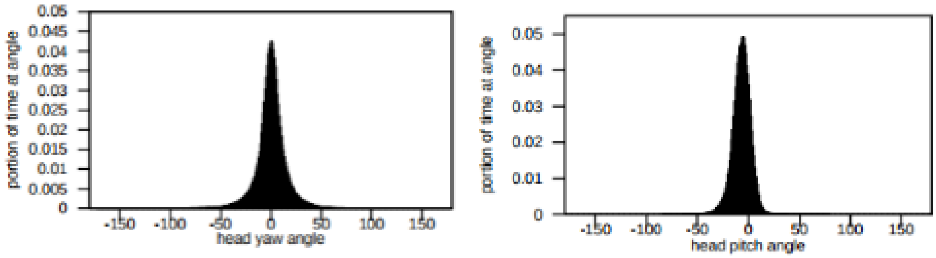


Figure 71: Head yaw- and pitch- angle. Retrieved of Disney paper of 1996.

To prevent the users' looking in only one direction there needs to be engaging things to look at in all angles and there needs to be support of cues, for example through sounds to lead the viewers' attention, encourage their curiosity and engage them to turn also to other angles. And through these cues the creators decide if they want to guide the user through the experience through giving them many cues or to let them explore their own way. Saschka Unseld said on his making of the VR 360 degree short 'Lost', "To embrace VR as its own unique medium, we have to let go of our almighty control of what the audience sees" (Unseld, 2015). Consequently, the director must also learn to let the control out of his hands and that is what makes VR a unique medium. Nevertheless, the director has to think at the same time about how to introduce key elements of the story, to at least try to lead the attention of the viewer, even if it is not crucial for them. "You can't blame your player for not looking in the right place or doing the right thing. It's our job to lead them through the story" ("How to Build Better Stories in VR", 2016). So, you need to direct attention to the main experience and give hints for the people to follow the action (cf. Pinson, 2016). On the one hand, you need to get the viewers curious and let them take an active role where they can experience the story, and on the other, after letting them enough time, to settle in. Then, you can get their attention back through a trigger such as a butterfly flying in front of their face (cf. Unseld, 2015). This can be seen as an action cue through movement. Besides movement, viewers are very sensitive to faces and gazes of people. If your character gestures in one direction, users are likely to follow this gaze. Other triggers can be visual or sound cues. This can be a narrative voice or noises. Also colors and lights can evoke meanings and can therefore lead to intuitive interactions (cf. Wray, 2016). The goal is to encourage the users to explore the scene through these cues. And as creator you should "Reward their exploration and give them a reason to explore the environment you've created" ("Lesson: Shooting in 360-degrees", n.d.). Another possibility to lead the attention of the viewer is through cutting. As the viewer is now able to choose where to look at, it can happen that when cutting to a new shot they are not focused on the main elements anymore because they turned around. Through using gaze detection “you can cut to the new shot and change its yaw value (the rotation of the 360° sphere) to match the object of focus in that scene to the direction in which the viewer is looking” (“The Cinematic VR Field Guide”, 2017, p.40 ff.). But while trying to lead the user through the story, one has to watch out that it does not make the story feel forced or too staged. Moreover, it should be remarked that too much things going on at once can also overstrain the viewers. Therefore, you must find a way between too much going on and a scene feeling empty and boring. “There’s a thin line where the story is interesting because there is a lot of things going on at once, beware of overwhelming from sheer information overkill. If there’s just one thing going on, the scene will feel empty and inauthentic. VR should emulate a real world environment” (Gajsek, 2016).

Furthermore, “A sudden shift from flat screen frame to a 3D immersive world can be confusing and overwhelming at first” (ibid.). Therefore Oculus Story Studio recommends a 30 second introduction video to adapt to headsets and familiarize with medium (cf. ibid.). “…we wanted to find something that took the audience by the hand and step by step, led them into the world rather than of just dropping them directly into the set and risking to overwhelm them” (Unseld, 2015). This need for finding a ritual for ‘settling in and setting the scene’ can be comparable with dimming the lights and with the opening of the curtains in cinema (cf. ibid.). “If you’ve done a good job with settling in your viewer and making him or she feel comfortable you’ve completed the first goal“ (Gajsek, 2016).

Another issue which should be defined before starting, is the User Interface (UI). The interface, such as menu or introductions in within the environment, should be chosen wisely and should support the story. Graphics or text can integrate in the story or integrated on top of it. Things like this must be defined in advance and choosing the right interface is often a difficult task, as there is not always the technical background and expertise available. But UI prompts are needed to progress and understand the story (cf. Wray, 2016). However, they need to be subtle so that the users still can experience the virtual world (cf. Bregman, 2015).

Like already mentioned, movement and faces are the things users are most attracted to. Concerning interactions with characters you can evoke authentic emotions if you use characters that look directly at the viewers. “This is a perfect example how VR has the power to break through the 4th wall” (Gajsek, 2016) and the viewer feels more like participating the story from a first person perspective instead of a third person perspective where they take the role of the observer which is watching on as events unfold (cf. “The Cinematic VR Field Guide”, 2017, p.45). “Eye contact in VR is even more powerful than in 2D when drawing the viewer in” (ibid. p.45). To check on how your scene feels, you can put your head at the location of where the camera should stand and look around you. The shot experiences in an HMD feels pretty much like this (cf. ibid. p.45).

Unfortunately, interaction with characters is not yet explored in detail in 360 degree VFX videos. So, maybe the characters can let you interact because they lead you with their gaze, but interactions like talking or gestures are not possible in 360 degree video yet. But “With the immersive nature of VR it will become critical to provide viewers with some sense of agency and control over their environment and so this will become necessary and commonplace. A new type of storytelling will develop that integrates cinema, gaming, and interactive theatre” (ibid. p.45).

Besides interacting with characters, there are also situations in VR where the viewer should not be in the center of attention.Therefore, it makes sense to use different perspectives for different intentions (cf. Gajsek, 2016). “The ruleset for the perspective isn’t strict. It does not say that it’s always from the POV of one person, or that it’s always from a specific height. What it does say is, ‘Here’s the interesting thing you’re supposed to be looking at and here’s how we’re driving the story, between cuts” (Robinson, 2016).

And real-life measurements help to adapt in the real world. Consequently, it is advised to use the real-world scale in VR experiences (cf. Wray, 2016). So, changing for instance the height of trees can confuse the viewer if it is not intended to evoke a feeling where the user should feel small or really huge.

4.2.2 TO BE AWARE OF

Two subjects that should also be considered in pre-production are stereoscopic capture and parallax. If one decides shooting in stereo, one needs to be aware of its consequences. “One challenge is that the traditional VFX pipeline has to be transformed to the VR mode with its 360 degree stereo views” (“ILMX Lab and VR : Media & Entertainment Technology”, 2016). So, there is also the possibility to shoot a 360 degree video in stereo to provide a greater depth perception. Together with spatial and temporal resolution of current HMDs this can provide a greater sense of presence. But there are some difficulties that come with shooting stereo. One of them, is that you need to train your artist “to think in terms of left eye and right eye” (Robinson, 2016) and “how to be efficient with roto and in how to extract track” (ibid.). Another issue with stereoscopic shooting is if you combine live footage with CG then there is a difference in the stereo. As the CG material renders “mathematically perfectly right out of the renderer” (ibid.), filmed content has still “a lot of physical realities that come to play ” (ibid.). And then dealing with stereo for spherical projection is also a subject which needs to be considered. There need to be methods to check and fix stereo in an efficient way (cf. ibid.). Moreover, stitching and also post-production with stereo footage is really difficult and in addition you are using more cameras which increases the amount of data as well as possible sources of errors.

Another issue is parallax. Parallax is always created whenever there are multiple cameras and there is movement or rotation. To prevent parallax you need to find the point in the camera where all light rays come together before being captured by the camera. That is the point where the distance between camera and object does not change at all. This point is called the no-parallax point or entrance pupil (cf. “State of VR | CHAPTER 1 / THE BASICS”, n.d.). When a camera does not rotate along its no-parallax point there will be difference in each image concerning the relationship of the points in the scene. And if parallax differences occur close to the edges of the images, it can happen that they can be seen as ‘ghosts’ in the stitched image. ‘Ghosts’ are objects that appear multiple times in different spots that are removed completely or are only half visible. Often, it is really difficult to match a picture well when a parallax error is captured (cf. ibid.). Concerning VR, capturing parallax is unavoidable because the no-parallax point is within the lens. Therefore, it is never possible to align cameras at this point and “each image will have small differences in the relationship between points in the scene” (ibid.). The only thing which can be controlled through the compound of the rig is how big the parallax errors will be. Instead of trying to remove parallax you will need parallax management (cf. ibid.).

Figure 72: Example for parallax.

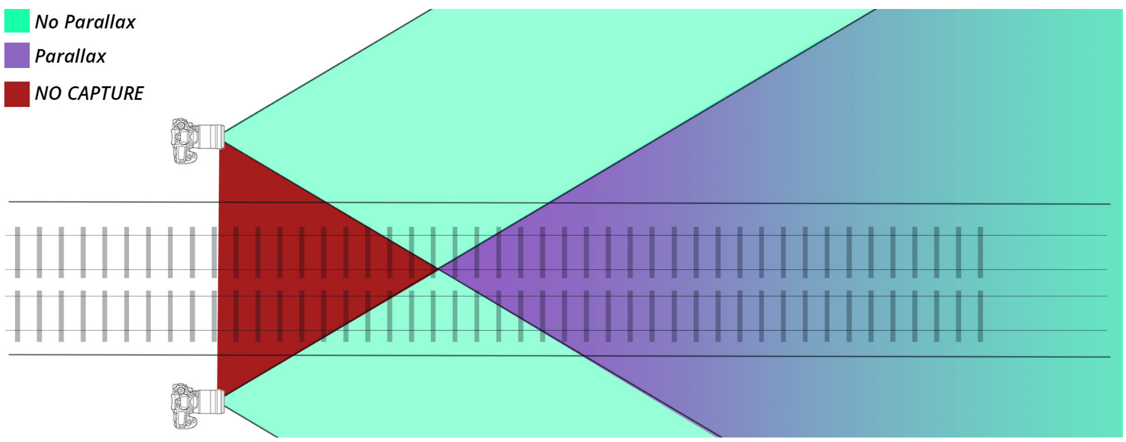


Figure 73: Visualization of the camera arrangement and highlighting of different areas.

The further away an object is, the smaller the parallax. And the farther away the cameras are from each other, the bigger the area of parallax. These features can be seen in *figure 72* and *73*. There are two images that have been captured from two cameras on each side of a train station. As you can see, the foregrounds differ wildly, but in the background the sun and the clouds seem quite identical. In *figure 73* can be seen that the parallax is the strongest in the middle of the images at the foreground (cf. ibid.).

Therefore, you need to make compromises with your camera rig and adapt it in a way to minimize parallax as much as possible but also provide an adequate sensor size and an appropriate amount of cameras for the purpose of your project.

4.2.3 CAMERA SELECTION

Before starting with shooting, you should also consider with what camera you want to shoot. So, as there are several cameras and rigs out there you have to consider a camera and rig solution for the need of the project. What is important? Budget? Good stitches? Special features? “What is on your personal list will dictate what camera configuration you go with” (Coulombe, 2016). But it is important to choose a camera and know the footage you will be working with, before you get into post-production. Also using identical cameras in a 360 degree rig with identical settings makes it easier to get the material together afterwards. But in case of using different cameras, you need to think about the consequences in post as well. As it is important that in a scene every camera has the same setting, cameras like the Jaunt ONE (J1-24G) are better to use because they provide the so called genlock option which is able to synchronize the timing between all cameras. GoPros, in comparison, are small and lightweight but do not have the advantage of a genlock feature and they use auto-exposure. So, you have to be aware that the different cameras have different implications for stitching in post-production and that matching the scenes of two different cameras can also be a challenge (cf. Coulombe, 2016).

Before starting shooting you should also consider your lenses. As VR rigs need wide lenses, there are most commonly spherical Fisheye lenses used, that are able to capture up to 180 degree and sometimes even more. These lenses collect all the light from around them and focus that light as a circular image on the sensor of the camera (cf. “State of VR | CHAPTER 2 / CAPTURING 360”, n.d.). But as sensors are not round, the area that is not “covered by the lens will be wasted resolution” (ibid.). Fisheye lenses were normally designed for taking photos, what means that their circular images were made to fit inside a 3:2 ratio[9] sensor. In video cameras the sensor’s ratio is often 16:9, meaning that the image gets cropped a little more. To counteract the lost pixels, cameras

9 Aspect ratio, defines the relationship between the width and height of an image.

using fisheye lenses are sometimes rotated to shoot vertically. Like this, the lens still captures 180 degrees of the vertical edge of the panorama (cf. “State of VR | CHAPTER 2 / CAPTURING 360”, n.d.).

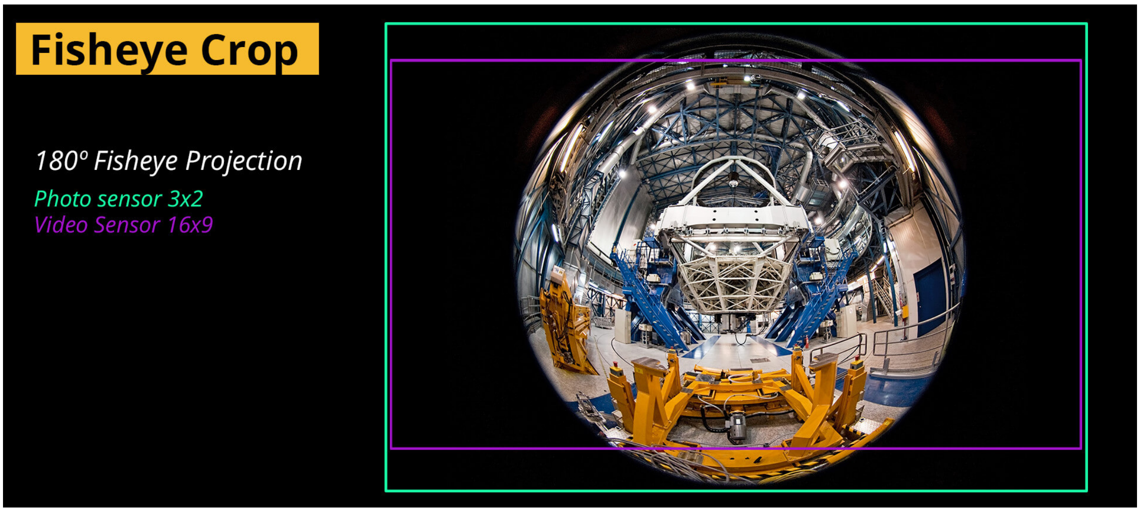


Figure 74: Fisheye crop and differences between photo and video sensor.

You should also consider shooting with a camera with a large HDR range and low compression. As in VR shootings light rigs are not possible because they would be in the scene, VR has to deal with situations that have large differences in brightness, such as for instance in outdoor situation. The higher the High Dynamic Range, the more freedom in color correction will be. Moreover, depending on which camera you chose, you can avoid clipping and heavy compression of the footage (cf. “State of VR | CHAPTER 2 / CAPTURING 360”, n.d.).

Thinking about the best way to arrange your cameras in a rig there needs to be a lot of research and considerations. Best, it should be a stable rig as small as possible for minimizing parallax. Another thing which is necessary is that you have enough overlap between the cameras, but on the other you try to keep the number of cameras as low as possible to keep the amount of data low as well as the rig weight and to get fewer seams, that need to be stitched afterwards. When using more cameras you will get more seams but fewer areas with errors. Fewer cameras will have larger stitching errors but fewer seams. So, one has to decide what is best for the individual project. In the following *figures 75* and *76* you can see the comparison of seams when using three and six cameras (cf. “State of VR | CHAPTER 1 / THE BASICS”, n.d.).

Figure 75: Stitch with three cameras.

Figure 76: Stitch with six cameras.

For putting the chosen cameras on a rig some important factors need to be considered. “The most important factors for rigging multiple cameras are stability, repeatability and accuracy” (“State of VR | CHAPTER 2 / CAPTURING 360”, n.d.). A rig must be robust enough to allow changing of batteries, memory cards and lenses during filming without altering the arrangement of the cameras. “Adequately allowing access to the cameras once they are mounted is vital, so that lenses, batteries or memory cards can be replaced during filming. Ensuring a rigid and repeatable mounting point is critical” (ibid.). Moreover, it would be helpful if the cameras can be powered externally to avoid one camera shut down while shooting and then the whole scene needs to be reshot because a part is missing. ”This is a very real concern with GoPro cameras that have a limited battery life” (ibid.). Another feature what would be useful is an external monitoring of the unstitched cameras to check on them if they are still working, if an external battery is not possible as well as control the seams and that no action strays too close to the edges and “that primary or pivotal actions are indeed captured as intended” (ibid.). Besides all that, the goal for camera rigs with multiple cameras is also parallax management. Therefore, the design of the camera array should try to keep all of the cameras “as close together as is physically possible” (“State of VR | CHAPTER 1 / THE BASICS”, n.d.). But when doing so you need to be aware that “the closer the cameras are to each other, the more cameras you need to cover the full 360°, and the smaller they physically must become” (“The Cinematic VR Field Guide”, 2017, p.23). And if the cameras get smaller also their sensors become smaller what means bad image quality and low light sensitivity. Therefore designing a proper VR camera is a game between optimization and tradeoffs (cf. “The Cinematic VR Field Guide”, 2017, p.23). In this category GoPros are an advantage because they are really small and can be kept closer together than for instance DSLR cameras. But on the other hand, one must also be aware of that if the cameras are arranged close together, they will produce more heat. Therefore they need to be checked during filming if they did not shut down because of overheating (cf. Bernabei, n.d.). “Arranging cameras in an array, or rig, is a simple concept but it takes some careful planning to make the most of the gear available” (“State of VR | CHAPTER 1 / THE BASICS”, n.d.). So you need to sketch out a layout and do a lot of try and error until finding the perfect solution. Another possibility would be to take and commercially established rig. There would be the advantage that already people tested the rig and maybe stitching software comes with it.

4.2.4 TESTING

“Fail fast and get learning” (“How to Build Better Stories in VR”, 2016). Doing tests and trying different approaches for several things is important at every stage of production to learn and get the best out of your project. These are also the advices of a lot of VR creators. Dejan Gajsek, VR storyteller recommends, “Make mistakes because we will either learn something that doesn’t work or we’ll find an ingenious solution” (Gajsek, 2016). And Framestore VR Studio’s Creative Director and CG Head Andy Rowan-Robinson notifies, “There’s always new challenges that we’re constantly coming across because the premises are always changing and new hardware is always coming out. There’s always new things to pick up and learn and new things to take advantage of” (Robinson, 2017). Resh Sidhu, also a creative director from Framestore VR Studio, mentions, “You will certainly need to be flexible as the creative will change. It’s about failing fast and prototyping early – only then will you be able to deal with the unique challenges this nascent medium presents” (Robinson, 2016). Joergen Geerds, CEO and creative director of KonceptVR says, “Just be experimental. Do test shots. It may be crummy quality at the beginning, but it teaches you all about how you place the camera, how you move it, how you tell the story, what makes an interesting frame, and how to compose the shot in 360” (Pinson, 2016). Sam Gage of The Third Floor advices besides the trying and failing "Go for quality over length. No one likes a VR experience that's crap and takes ages" ("How to Build Better Stories in VR", 2016). So, it is better to create good quality content which is short, but really good, instead of a long experience where no one stays excited and engaged to explore the virtual world. Also test evaluations during post-production are very useful. Through that you can test peoples' reactions, ask how they felt the experience, check if they get motion sick, where they look at and if they get the cues you placed during the story. It is important to do user tests with random people who have nothing to do with VR because they are the best to check on all these things. "Ideally, we should show our work to random people that we don't know since they have no vested interest in outcomes and won't stroke our ego. Their observations, feelings, and especially reactions watching our creation are pure gold" (Gajsek, 2016).

4.2.5 PREVISUALIZATION

One main task which should be developed during pre-production is, after creating a story, visualizing the ideas. Due to it is difficult to storyboard a story which should play in 360 degree space it is useful to create a previs in advance. It is ok to storyboard the main idea, but then it is useful to convert this storyboard into 3D, into an animated visualization. There you can check on your ideas, try things out before shooting, test if people could get motion sick, if the attention is directed in the right direction and you can check out if your scene feels to empty or claustrophobic. Moreover, you can check on that already in the end device for example a mobile VR HMD. And one should be prepared before the actually shooting because shooting VR must take a lot of decisions in advance to it get all smooth. You have to be aware of the timing, placing of characters and objects and with VFX you have to be even more aware because you need to think of where to put your 3D elements or effects. To create a previs you can, on the one hand, already shoot some easy test with for example a 'cheap' camera such as the Ricoh Theta S which is fast and you can see a preview on your smartphone and then do some quick tests in post. On the other, you could also create a previs in Maya or in any game engine to visualize your story. Like this, you can check on blocking or where the seams of the cameras will be and how you need to position your characters or objects. Sure is, that at this point, you will recognize

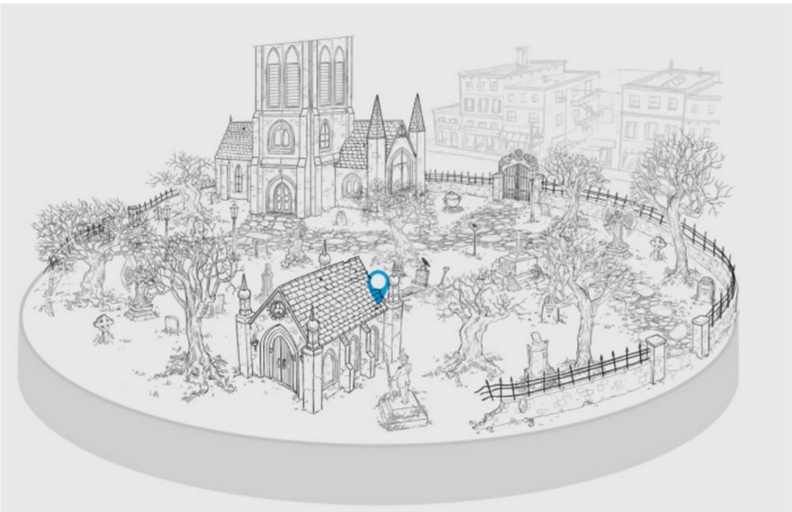


Figure 77: 360 degree story board.

if the experience works in 360 degree world or not. Because you will be able to feel the scene, you are more likely to understand what must be changed to ensure an optimal, successful experience for viewer.

4.3 PRODUCTION

“When shooting VR, you have to constantly consider the technology“ (Bernabei, n.d.). Everything is still evolving and there are always new generations of HMD or capture techniques.

Even though 360 degree video with VFX has a lot of similarities with the normal VFX workflow, shooting is an exception. “Shooting 360° VR is not just slightly different from a standard shoot, it’s completely different. The success and cost-effectiveness of the project completely depend on the planning” (ibid.).

4.3.1 NO HIDING

While shooting for VR there is one main issue, you cannot hide anywhere on set. “…with the 360 degree view, there is no such thing called “behind the camera” (Ergürel, 2016). That applies to the whole crew, including director, camera man and also actors, as well as for lighting, rigs in any kind, vehicles or pedestrians. This way of shooting comes with a few challenges, such as for instance that the director cannot be in the room with the actors to check on their play and text or need to give them instructions. So, the director needs to trust the actors and they have to be able to fulfill the instructions without him being near. “This means that they have to rely on acting more to convey their vision. The dynamic between the director and the actor is more akin to theater” (Bernabei, n.d.). Therefore, the action around the camera must be carefully planned and choreographed before. In the work as a director you “find yourself going back to exploring what works best in a real-world framing — almost like you are directing a play in an intimate theater” (Altman, 2016). Jaunt Inc. advices, “Those that embrace this new canvas without trying to force their 2D sensibilities onto it will be the ones that succeed and contribute to the development of the new language of cinematic VR” (“The Cinematic VR Field Guide”, 2017, p.35).

Concerning the actors they need to bring some qualities when shooting in VR. They should understand the geometry of the shot as well as need spatial awareness. As there is no director on set, it is the duty of the actor to carry his vision and intent without his presence (cf. Bernabei, 2016). “Every aspect of the “scene” must be known, rehearsed and memorized before you start” (Juillet, 2016). Another thing where you have to be aware of is the stitching crossovers. You need to think about where to put your cameras as well as where you are staging the actors because they should not pass the stitching crossovers. There is an approximately one and a half meter glitch zone around the rig. That means, if a person is seen by more than one camera it will be doubled in the stitching program. So as the camera is everywhere the actors have to be careful where they walk because of the seams. It would be better to avoid these, especially in close ups. And what applies for the director, also applies for the rest of the production crew. Cameramen cannot control the camera all the time and cannot intervene when something does not work. Also set-designer and make-up artists maybe need a long time to check on things because they might be out of the scene and have to overcome long ways to get to the set. It is certain that everybody needs to vacate the set and try to hide behind things or leave it in long-range. “It’s always a game of hide and seek when you’re shooting a VR scene“(“The Cinematic VR Field Guide”, 2017, p.35). So you need to keep that in mind when shooting in VR. As a rule Joergen Geerds from KolorVR affirms, “If you see the camera, the camera sees you” (Pinson, 2016). And not only persons need to be aware of to be seen by the camera, you also have to be really careful where to put your whole equipment, lighting rigs for example. “Space is a critical component of VR shoots” (Bernabei, 2016). You need to be careful with placing things and actors because of the stitching seams, as already mentioned. These are the critical sections and therefore, “you have to draw invisible lines in space and remember where they [the seams] are in your head” (ibid.). “When certain equipment (like dolly rigs, for example) are unavoidable, they will need to be painted out in post” (Coulombe, 2016). But especially for lighting, one needs to get creative and often practicals are used to avoid lighting rigs. So, you work with light sources that can integrate in your scene, such as lamps that fit in the place or windows with natural light. The goal is to hide all light sources organically in within the scene and try to take advantage of natural light. But as there are no strong light sources like from normal film equipment, you have to watch out for noise if you are not able to afford a high-end cam (cf. Bernabei, 2016). If that is the case, there is still the possibility to paint some light rigs out later in post-production. This means, that it is considerable to block the scene exactly in previs and have the editorial in mind while shooting (cf. “NOTES ON VR – 360 Shooting and Points of Interest”, 2016).

Two other things that have to be considered in lighting for shooting VR are lens flares , specular highlights, reflections and exposure. Because of using multiple cameras it can happen that exposure varies in different sections of the environment. That occurs, for example, when one side of your room is dark and the other side is in very bright sunlight. Generally, the camera rig should allow individual exposures and if you set them on auto they will adequately expose the scene through each camera. “The stitching algorithm will then blend these exposures to make for a seamless stitch” (“The Cinematic VR Field Guide”, 2017, p.46). In *figure 78* you can see such exposure differences in various parts of the image. The second *figure 79* shows a corrected exposure version.

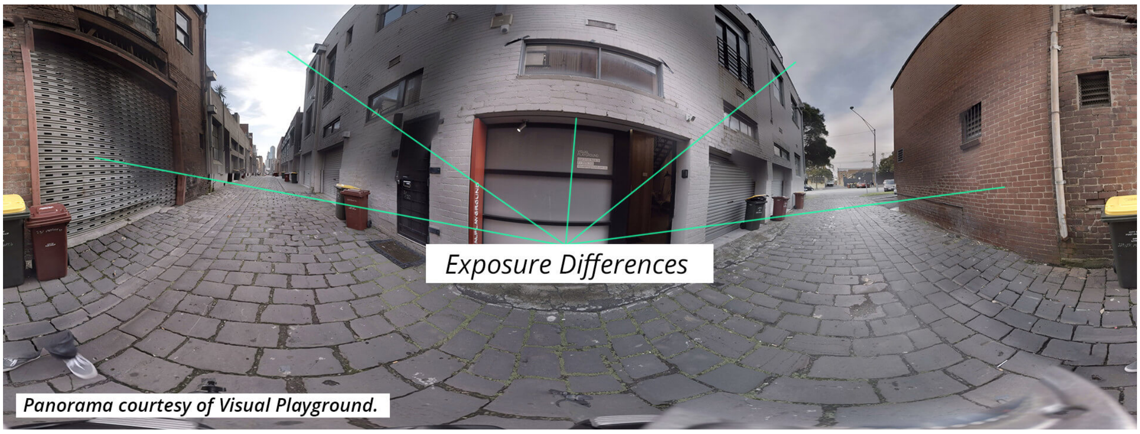


Figure 78: Exposure differences in example image.

Figure 79: Corrected exposure in example image.

And also flares, as well as specular highlights and reflections, can be a problem if they only show up in a few cameras. In VR it is difficult to use, for example, a flag to block the light out because it will be seen in the camera. You can try to minimize the flares, for example, by rotating the camera or you use objects that seem to fit in the scene as an 'organic' flag. With VR you need to get creative at certain points. If there is no solution for the flares on set, there is still the possibility to paint them out in post if they are too distracting (cf. "The Cinematic VR Field Guide", 2017, p.47 ff.).

Another possibility when shooting with a static camera or a MoCo rig and if you have the control of the scene and in this scene there are not many objects moving or changing lights, then you might be able to shoot in two halves. So, first you shoot the scene in 180 degree on the one side and lights and crew can be at the other side. After that you can change both sides and shoot the other 180 degree. Both times you capture the full 360 degree even when people and equipment is in the picture, but like this, it is later easier to composite the two halves together in post-production with a proper blend (cf. "The Cinematic VR Field Guide", 2017, p.36).

4.3.2 TECHNICAL CONSIDERATIONS

When you already decided in pre -production which camera and lenses you want to use and how you arrange your cameras on a rig or array, you need to check on how to handle the technology on set.

It is important that for one shot identical cameras with identical settings are used. So that they all capture everything at the same time you need to ensure that there are not even slight offset frames because then the action in your shot would not match between the several cameras (cf. “State of VR | CHAPTER 2 / CAPTURING 360”, n.d.). In *figure 80* you can see such a timing mismatch.

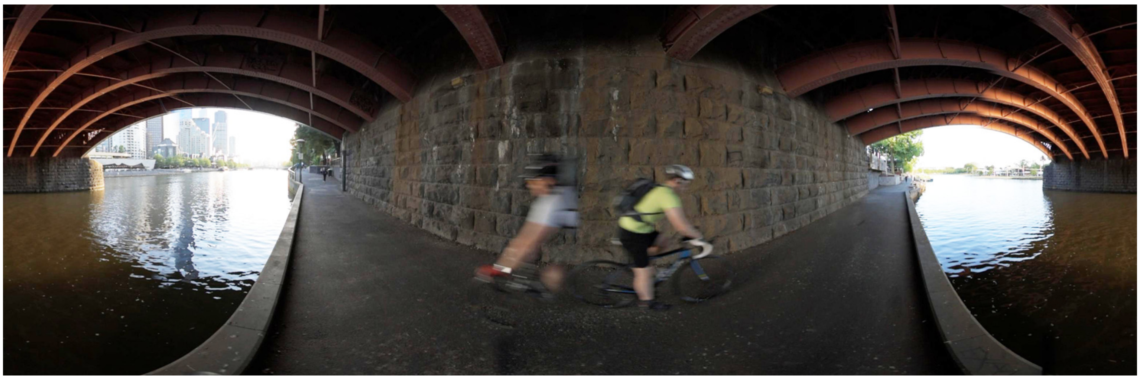


Figure 80: Timing mismatch.

Like mentioned in the pre-production section, there are large professional cameras available that have the feature of genlock. “In a genlocked system, the cameras are all connected with a cable that sends very accurate timing information to each camera and allows them to record their frames at the same time” (ibid.). But also synchronizing without genlock can be possible even though it is harder to do. You can use visual, audio as well as motion cues and also time-codes to synchronize after shooting.

As already mentioned in the storytelling section, the camera is comparable to the audience when shooting. So to say, the viewer takes the place of the camera. Consequently, you can check on the view he will see in the end through placing your head at the place of the camera. “You can either position the camera as the center of the action, and let the characters react towards the viewers, as if they are part of the story. Or the camera could be used like in a documentary and position the viewers as an outside observer—or put in another way “a fly on the wall” (Ergürel, 2016). So, the rig height plays an important role for the intention of your story. “Generally the camera is placed at average human height of around 5’-10” (“The Cinematic VR Field Guide”, 2017, p.42) except you want to provoke a special feeling of being extremely huge or small. Deniz Ergürel, tech journalist advices, “Find the sweet spot, depending on the action of your story. Not too close, not too far. Not too low, not too high. Be the eyes of the viewers.

Take them to places, moments, events to experience the things that they may not experience in other ways" (Ergürel, 2016).

Considering the distance to the subject there are some issues one need to be aware of. All in all you can say, "the closer you come to camera the closer the cameras must be to each other" ("The Cinematic VR Field Guide", 2017, p.23). The issue is that when one camera sees an object, but its nearby camera does not, you will get problems with synchronizing and stitching the footage. Especially in a close up this effect is critical because it can happen that only one part of the face is visible in one camera but not in the other (cf. ibid. p.23). Oculus recommends a minimum distance of 0,75 meters which can be compared with about 2,5 feet before the user starts going cross-eyed (cf. ibid. p. 39). From there until 30 feet it is possible to put important content that should be in focus of the viewer's attention, and after 60 feet there is "virtually no perceived parallax" (ibid. p.39). But the minimum depth limits differ from VR camera to camera and some of them even have a minimum depth limit until five feet to get the stitching properly done (cf. ibid. p.39). "A way around these minimum distance limits is to shoot the main environment in 360° 3D with the VR camera and then use a traditional stereo camera rig to shoot the actor green screen in the same environment and lighting and then composite them into the 360° background in post" (ibid. p.24). If an extreme close-up is needed, this would be a solution, but this way would demand additional equipment and more time (cf. ibid. p.24).

"The bigger the field of view, the wider the image you see through the viewer, producing less of a "ski mask" effect" (Korolov, 2016). And also immersion increases with a wider field of view. The FOV depends on the HMD you watch the experience in and normally as a creator you should keep the action within 150 degree in front. These 150 degree assemble through approximately 90 degree FOV of the HMD plus the additional 30 degree on each side of peripheral. As a result you get 150 degree (cf. "The Cinematic VR Field Guide", 2017, p.38). "You should endeavor to keep the main action within these limits" (ibid. p.38).

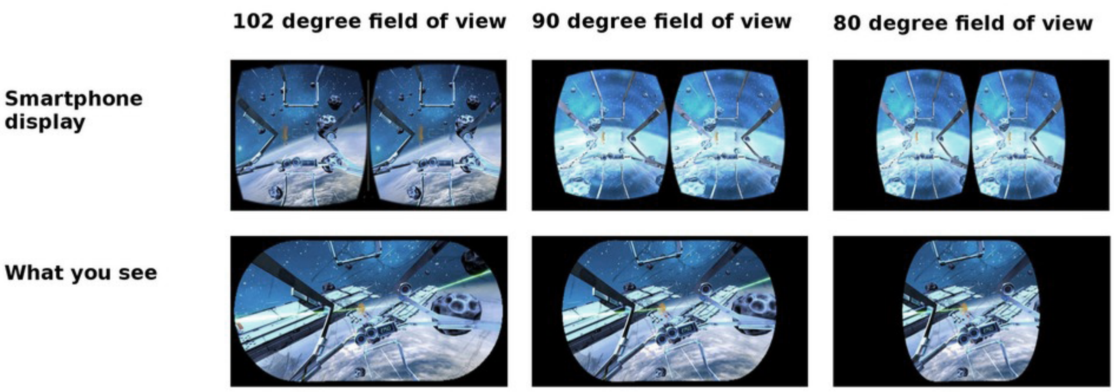


Figure 81: Different FOV.

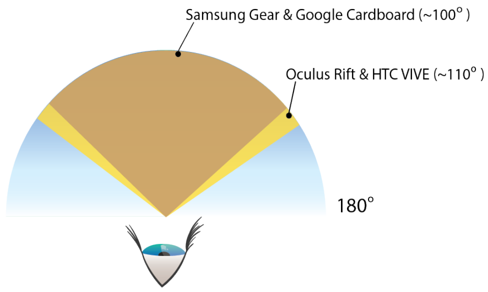


Figure 82: FOV of different HMDs.

Using a higher framerate makes a more comfortable experience for the users. The goal is that a picture faster updates than the brain can spot the difference to the picture before. The higher a framerate the greater is the chance that the viewer can feel immersed (cf. “State of VR | CHAPTER 2 / CAPTURING 360”, n.d.). “Do optimize performance quality. It doesn’t matter how cool your experience is if it makes viewers nauseous. Aim for a minimum 60/fps, but ideally 90. Anything lower and the viewer will not feel the sense of immersion” (Robinson, 2016).

Concerning resolution, there is also the aim to get a resolution as high as possible. When for instance a 360 degree video is shot in 4K, only about 480p[10] resolution can be seen by the viewer. You can still reach an okay-level with 4K but 6K or even 8K would be better. So, to get HD-level sharpness for a 360 degree video “the resolution of the entire surrounding video must be around 8K or even more” (“VFX for 360 VR, and why you are not prepared for it (Part 2)”, 2016). The problem with this resolution is that you got really huge size files and as you have multiple cameras that is an amount which is just too huge at the moment, even for the fastest machines (cf. “The Cinematic VR Field Guide”, 2017, p.23). So, post-production including editing, compositing, color correction and CGI with this file sizes get difficult. And even if the final file is compressed for delivery, the bandwidths of every consumer can be different and is also not capable of delivering such high file sizes. The “bandwidth gap here severely prevents user experience improvement“ (“Virtual Reality (VR) and 360 Videos 101 — A Beginner’s Guide”, 2016). Consequently, there must be still compromises be made until this gap gets smaller. The Jaunt for instance limited their resolution they “output to 3840 x 3840 stacked left/right eye equirectangular stereo 3D at 60fps” (“The Cinematic VR Field Guide”, 2017, p.23).

At this point foveated rendering could improve the streaming of such an amount of data. It is a streaming technology for 360 degree videos. With foveated rendering only the visible section of the 360 degree video is streamed in high resolution and the nonvisible sections only in low resolution. Through the head movements of the user the direction

10 Display resolution. 480p refers to the vertical resolution (640 x 480). In comparison, 4K has approximately 4000 pixels horizontal resolution.

which should be shown in high resolution is detected and when the user changes the direction the low resolution stream switches to a high resolution stream. Companies facing this technology are Visbit and Oculus Dynamic Streaming (cf. “Virtual Reality (VR) and 360 Videos 101 — A Beginner’s Guide”, 2016).

As the audience in 360 degree videos is not able to move on their own, the only possibility is to let them move with the camera. You need to address the sense of balance of the user and avoid any slackening during head movements in the VE, otherwise it can cause nausea and the experience is not enjoyable for the viewer. Therefore, when doing a VR experience you should guarantee that the user is not getting motion sick. The safest and easiest way is that the camera is not moved and stable at one position. But a moving camera is also possible. But you need to be careful with acceleration or deceleration as well as with sinuous movements. Best is in a straight line, constant, subtle and steadily on a drone or cable cam. “Use long shots. They’ll make the user more comfortable and it will be far less jarring than jumping around every few seconds as you would in a normal piece” (Robinson, 2016) remarks Lucien Harriot of Mechanism Digital. One major advice is also trying not to rotate the camera. Especially panning, tilting and rolling can cause nausea and make the user feel disorientated. Christian Back of Psyop advices “Don’t rotate the camera, that’s bad. I haven’t seen anybody pull that off without making users sick. Beyond that, I’m hesitant to say don’t do something because I think it’s all worth trying (ibid.). There are some advices and guidelines to minimize motion sickness, but at the same time they can be broken if you know them. In some experiences for instance, such as a roller-coaster ride, a little motion-sickness can come with. After shooting, there is still the possibility of trying to stabilize bumps and the horizontal lines with post-stabilization. More cameras also mean that more memory cards are needed for the shooting. One should plan enough data storage ahead (Coulombe, 2016). With more data, also the points of potential failure increase. Therefore, using a well-organized system for data storage management is crucial when working with VR and has high priority. More cameras not only connote more data, but also longer time to double and third back-up (cf. “State of VR | CHAPTER 1 / THE BASICS”, n.d.).

Moreover, live preview on set is not that easy with multiple cameras and they need a lot of processing power on set. And also the stitching algorithms still need to be figured out. So, as alternative it is possible to put, for example, a Ricoh Theta S somewhere near your camera to stream a live-stitched image via Wi-Fi to your phone or other mobile devices. Like that, you can at least check on the scene and actions that happen (cf. “The Cinematic VR Field Guide”, 2017, p.37). Of course, this possibility is not the best, but if you know the limitations, it works depending on what you need for your individual project. In the following case study in chapter five the project ‘HELP’ will be introduced. There, the team from The Mill developed a special live-stitch method for on set review. So, you can also develop custom stitching methods for the purpose of your project.

4.4 POST-PRODUCTION

Daniele Bernabei, Research Engineer at Foundry shares in his article 'What they don't tell you about 360 degree VR production' some experiences he had. Considering post-production he notifies, "What's the most important thing you need to know about VR post-production? Take your most pessimistic estimates of how long it's going to take, then triple them. If you want to achieve cinematic quality with no artifacts around the seams, it's going to be expensive, and it's going to take time" (Bernabei, 2016). Like he remarks, post-production is one of the most challenging parts in VR. Because of the high amounts of data and because there are no fully developed tools that are specialized for the needs of VR, it is a process of a lot of trying and pushing against boundaries until there will be more new tools, like for example Nuke Cara VR, that alleviate the whole post-production process. Chris Healer, CEO of The Molecule states, "It's really easy to get it 80% of the way done, but the last 20% can be difficult and expensive" (Coulombe, 2016). Especially stitching or finishing can be sloppily done and lead to VR experiences that are not properly done and therefore not provide the best possible experience for the consumer. So, for the quality of your project, it is important to do these steps during post-production properly.

Before going on further in to post-production processes, the format you mostly work in VR should be presented. Normally, a spherical image is stretched out onto a flat plane to an equirectangular image, also called latlong. Latlong is the abbreviation of latitude-longitude. A latlong has always a ratio of 2:1 in width to height and the good thing about them is that they only have one seam on the edge of a longitude line as well as two others on the top and bottom line of the image where the image turns into one point (cf. "Guide to VR", 2015, p.12 f.)

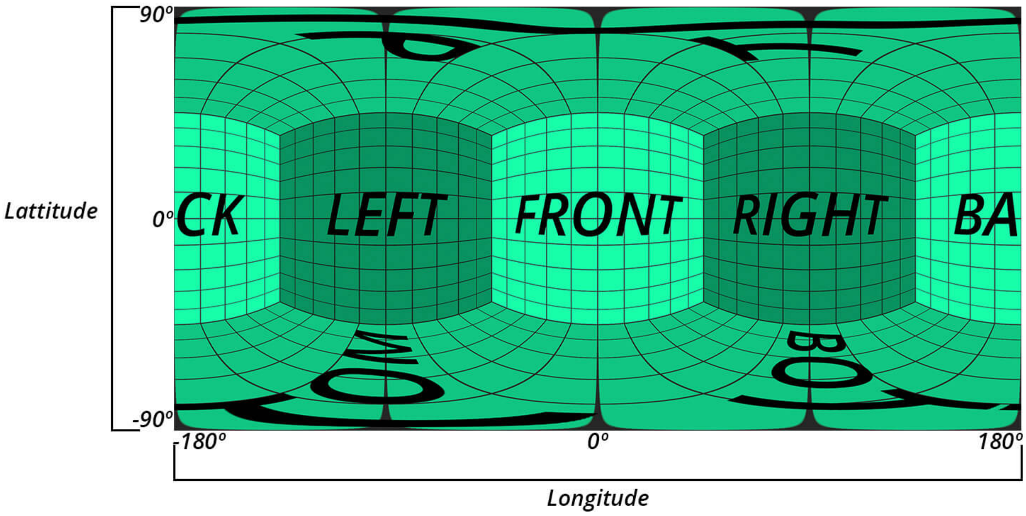


Figure 83: Equirectangular image.

“The issue with latlong images is that they are very distorted; 66% of the image represents the top and bottom poles,…” (“Guide to VR”, 2015, p.6) which is normally not that important because the poles are mostly not the focus of attention. But still “there is a significant distortion across the image” (“State of VR | CHAPTER 1 / THE BASICS”, n.d.). In the following *figure 84* you can see the areas where distortion occurs and how the areas look like without distortion.

Figure 84: Latlong distortion and how areas look without distortion.

Latlongs are a format to store spherical images and have an easy look on them to see what the scene consists of in one single image. To present the image in an HMD, it must be converted back to a rectilinear view (cf. “State of VR | CHAPTER 1 / THE BASICS”, n.d.). “Fortunately, because of the consistency and standards in place for going to and from a latlong images, this is a trivial task in most software” (ibid.).

Another possibility to represent a spherical image besides a latlong map is a cube map. Cube maps are often used in games. In this method the spherical image gets converted into six equally sized squares of the inner side of a cube which enable a view of every side such as front, back, left, right, top and bottom (cf. ibid.). An advantage of cube maps is that they have less distortion than a latlong because they appear as 90 degree FOV image (cf. “Guide to VR”, 2015, p.7). But they also have far more seams that need to be stitched than a latlong. You can see an example of a cube map in *figure 85*. But as already mentioned, the common format for representation is normally a latlong.

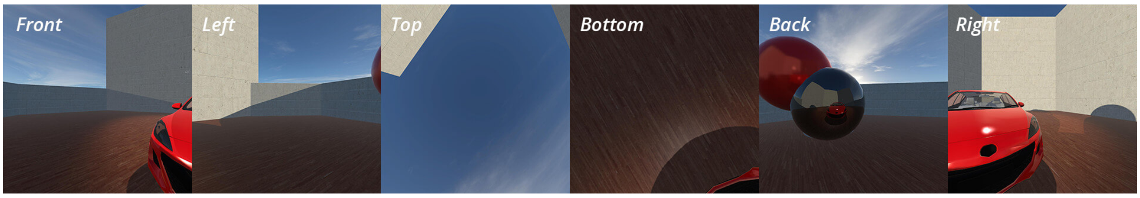


Figure 85: Example for a cube map.

4.4.1 STITCHING

Before now starting with post-production, you need to plan at least a few days of copying your footage to the server on which you are going to work (cf. Coulombe, 2016). It is important that all of your footage is synchronized. If you did not use cameras with genlock you have to first do that, for example, in After Effects with mentioned methods like sound or visual cues or the time code. Some stitching software also allows doing synchronization as part of the stitch. Most important for stitching is that all cameras have the same frame rate and all cameras have the same timing of capture. One must be aware on shooting that all cameras work identically, but also during copying processes one need to watch out that the footage is not corrupt (cf. “State of VR | CHAPTER 3 / THE STITCH”, n.d.). That is the reason why it is crucial to work organized and label all of the camera footage so that it can be found immediately. So, “Stitching is as much an exercise in project management as it is a technical adventure” (ibid.).

After all the data management and synchronizing you can start with the stitching process. “Stitching in VR quite literally refers to taking all the footage from all the cameras in the rig, and arranging them into a single image” (ibid.). The stitching process consists of removing distortion, matching common features of different cameras and then aligning them into a latlong format, like explained in the beginning (cf. ibid.). There are a number of tools and software already available to do stitching. You can either go for automated processes of software like AutoPanoVideo or PtGui, but also a manual stitching in, for instance, Nuke is possible. In the beginning, you have to tell your software what cameras and rig you used. There are also some templates available for common rigs and with these templates you can already get a rough stitch (cf. Coulombe, 2016). You can also define your own stitching template beforehand and then use it afterwards in post. But there, the arrangement of the camera on the rig must stay consistent throughout all shots. The major steps automatically stitching software goes through are described below and the automatic process can also be supported by some adjustments by the user at some points.

Before starting, it is important to check on the names of all the footage because they need to be correct and appropriately allocated that the stitching software can find out which footage belongs together. After that, the first step of stitching is always removing distortion and creating an undistorted image. That means, to remove the curving of straight vertical and horizontal lines that is created by the fisheye lens. As several shots need to be combined an undistorted image is important in VR “to be sure that the proportions and relationships between things in the frame can be trusted and are reliable and that means them not skewed, literally, by the lens” (“State of VR | CHAPTER 3 / THE STITCH”, n.d.). Removing distortion often works as an automatic process and as you use a lens which is popular, there are also often preset values available for removing the lens distortion of the specific lens. An undistorted image looks like in *figure 87*. It is stretched out and the corners seem useless and one might crop them, but still they provide a lot of information, so they are kept during the stitching process (cf. ibid.).

Figure 86: Distorted image.

Figure 87: Undistorted image.

After the step of creating an undistorted image, similar features of different cameras will be used to match the different footages together. Defining a series of control points for the automated stitching is necessary. These points are points that are seen in more than one picture and therefore serve as clues for the stitching program. Feature points should stand out of their surroundings and need have unique characteristics to be identified easier. Normally, the software finds such feature points by itself, but the user is enabled to manually define them as well or to define points if it is too hard for the software to find some. Feature points are clues the software clings to and with these “the software will align them – warping the images so that the features are placed one over the other” (“State of VR | CHAPTER 1 / THE BASICS”, n.d.). That is the reason why an overlap between cameras is important, to have enough common feature points that can be used for stitching. “The different images will then be gradually faded from one to the other, usually with some degree of user control though always in a straight line.” (ibid.). The transition from one image to another is called ‘seam’.

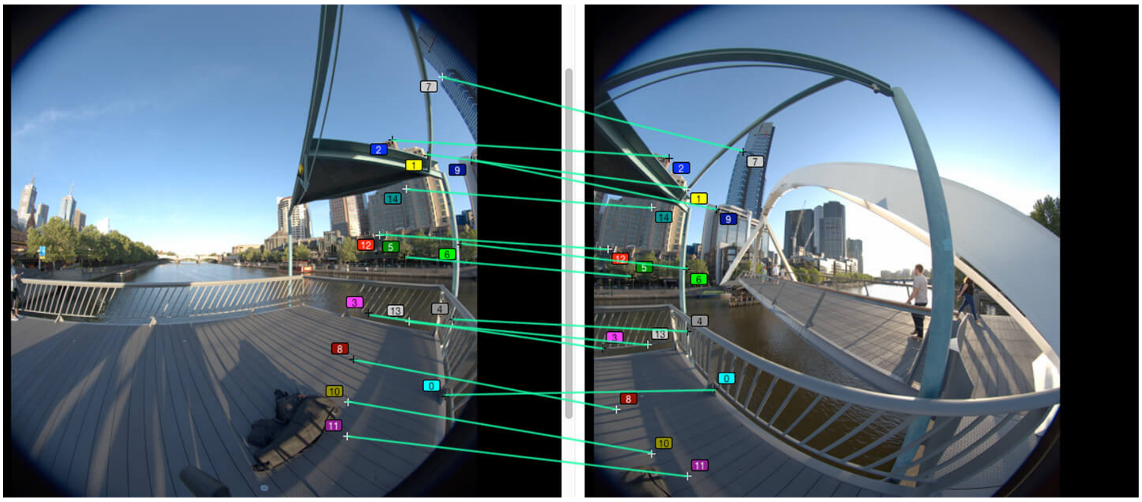


Figure 88: Similar feature points of two images.

Figure 89: Stitched image.

After stitching the panorama, the horizon line is often in a strange angle. So, this needs to be fixed before exporting the scene to prevent motion sickness. Before going into the post-production itself of the latlong scene, some software also allow to adjust exposure differences or have the opportunity to stabilize some camera moves as automatic processes. But it could be that these results are not optimal and then you need to take care of these issues after exporting in another program (cf. “State of VR | CHAPTER 3 / THE STITCH”, n.d.). For exporting your stitched footage, you need to choose the size of your final panorama as well as the export format. Then you need to wait until this is preceded and after that the footage can be edited in any editing program. One challenge with that is that you cannot see how the final image in an HMD will look like while working on it. But after a while working with a latlong format it becomes easier to read the footage (cf. ibid.). Moreover, some custom solutions are built where it is possible to check the footage in an HMD or where the latlong gets transformed in a format “that a viewer would normally see in the VR headset” (Coulombe, 2016).

Besides stitching your footage automatically, there is also manual stitching possible or needed if there are just too few feature points in the images. Manual stitching gives you more control over the single process parts. You can, for instance, decide where exactly put your seams and choose your favorite picture that should be taken for special objects. In addition, in a manual stitching process controlling exposure, color and stabilization can be faced in a more direct way as well as additional warping to counteract the effects of parallax is possible (cf. “State of VR | CHAPTER 3 / THE STITCH”, n.d.). Be aware of stitching stereo because you need to stitch the images of both eyes separately.

Some rules which you can already think about during shooting can ameliorate the whole stitching process afterwards if you follow them. One first thing is that you should plan your scene with no actor or objects crossing the stitching lines. Also, you can try to hide stitching lines, for example, in patterns of curtains or rugs. Another thing is that stitches get more obvious the closer an object is to the camera. Thus it is important to avoid close objects of interest falling across a stitch line (cf. “Lesson: Introduction to 360-degree video and virtual reality”, n.d.). So, all in all it makes sense to work around stitching lines to facilitate the stitching process afterwards and be able to create good and clean stitches. The crew of the design and motion design studio Tendril advices, “Do use the best stitching possible, as the better and cleaner your stitching, the more believable the world is. This is especially important for live action VR” (Robinson, 2016). After stitching you need to check on your final stitch if everything works out well and there are no mistakes or things that can destroy the immersion of the user. Things to be aware of can be if the right angles are provided in the image, if there is no moving object crossed by a stitch line and the object is cut therefore into pieces. After removing the camera tripod as well as crew and equipment in VFX and CG, there needs to be another check on the final image (cf. Coulombe, 2016).

4.4.2 MATCHMOVE AND RENDERING

After stitching before going on with post-production and the VFX part, the footage must be matchmoved if there is a moving camera in the footage. That means that the camera of the real live footage must be aligned with a camera in 3D space. With doing this it allows to position, scale, orientate and move 3D elements in within the environment in accordance with the real-live footage. “Although we started the whole process filming with many cameras, the intent was always to end up with an image that appeared to have been captured by one “super camera” (“State of VR | CHAPTER 4 / POST-PRODUCTION”, n.d.). In 3D space this is possible to do because you have “access to this ultimate camera rig” (ibid.). So, matching the footage and your 3D objects to this one ‘super camera’ is a challenge, but can be done through the transitional tracking data of the matchmove.

One program which provides matchmoving is SynthEyes. And “SynthEyes supports an entire workflow for stabilizing 360VR shots and inserting 3D objects into them” (“360° Virtual Reality Features”, n.d.). But even if there are some programs that support matchmoving, it is still a difficult task because in VR shots are often longer than usual and with these, it is even harder because you need to be precise in matchmoving that nothing is floating and the viewer gets nauseous. LiDAR can also be a support to get a better track (cf. conversation with P. Heinen, 2017). But also at this point, stereoscopic 360 degree is a challenge. So, one has to find temporary solutions that try to fix that problem with stereo. For example, trying to use the image streams as if it was monocular footage and then adapt the resulting stabilization to the both of the image stream could be an approach (cf. “What about Stereo 360VR?”, n.d.). When your footage is matchmoved and your 3D camera matches your 3D elements and aligns with the footage, you can render this whole scene. When using a static camera the step of matchmoving can be skipped.

If your 360 degree video should be prerendered then you need to plan a lot of time like for the data copying at the beginning. Prerendering enables higher-fidelity assets because you are able to render over a longer period of time, in comparison to real-time rendering of a game engine. Lucien Harriot of Mechanism Digital states, “Leave plenty of time for rendering as there’s always a lot more than you think. Between conversions, imports/exports, 4K frames and stereo, a 4-minute shot can take hours, sometimes days, to render” (Robinson, 2016). Inform yourself about the render settings that would be best for the needs of your project and wished output. As the website State of VR mentions “Rendering for VR is a topic that would need it’s own book, let alone a chapter” (“State of VR | CHAPTER 4 / POST-PRODUCTION”, n.d.). Important is that you use a render engine that supports spherical rendering. Vray, Arnold and Mantra, for instance, have a strong VR presence at the moment, but there will be probably coming more in the future (cf. ibid.). Also stereo rendering brings new challenges to this part of production because stereo footage needs to be rendered with two cameras, each one shooting different footage for each eye. More information about rendering is provided in the ‘Guide to VR’ of the Chaos Group Labs or at the website of eleVR.

4.4.3 COMPOSITING

After rendering, the phase of compositing starts. That is the part where rigs, crew, equipment or the tripod of the camera are painted out as well as where CG elements get integrated into to the rest of the real live footage. As for 360 degree video, there is still no comparable toolsets available that follow an intuitive workflow. Like in 2D compositing, there need to be other solutions to get the work also done in this new medium. Often 360 degree compositing is faced with solutions that work on top of traditional two dimensional images (cf. conversation with P. Heinen, 2017). Moreover, working in an equirectangular format entails a lot of unnecessary issues, such as for instance waste of computing power and storage and incompatible tools. So, working in this format which is distorted “can feel intimidating and frustrating” (Coulombe, 2016) because it is difficult to adjust precise effects due to the different capture resolutions between poles and center and you need to be aware that the pixels on the top do not match exactly the pixels on the bottom of the image. Therefore, as working in a latlong is difficult, you need to move from an equirectangular projection to a traditional perspective view, a rectilinear projection. Then you are able to work in a format where you can apply most of the tools you are also using in 2D. After editing, the comp must be again changed to the equirectangular form before final render (cf. “State of VR | CHAPTER 4 / POST-PRODUCTION”, n.d.). A transformation to a rectilinear projection can be reached through, for instance, a node in Nuke that warps the latlong “into something that a viewer would normally see in the VR headset” (Coulombe, 2016). Like this, it is possible for the artist to work in a more traditional perspective. Anyone can develop an own method of converting latlongs into a view that looks more familiar (cf. ibid.). That is definitely a step worth doing because you can keep on working in an image you are used to. Because of this shift in the perspective “any visual effects artist can get in there are start working with it” (ibid.), said Michael Clarke from The Molecule who developed this method for their compositing workflow.

In *figure 90* is an example of an image from the VR series ‘Invisible’ where the Visual Effects have been done by The Molecule. In this picture you can still see the camera rig in the bottom.

Figure 90: Image with rig on the ground.

With now switching the perspective to a rectilinear image, you can easier isolate the camera rig and paint it out like you would do it in a common workflow.

Figure 91: Removing of rig in rectilinear image.

After that the shape can be isolated and then reconverted back in an equirectangular image.

Figure 92: Isolating of the shape and then reconverting to an equirectangular format.

And then you get a latlong without a camera rig. This method also works for tasks like rotoscoping, painting and also tracking (cf. Coulombe, 2016).

Figure 93: Image without rig on the ground.

Shooting clean plates on set can be also useful for any removal of unwanted objects afterwards in post. So, for the camera rig it is recommended that you shoot the ground that your rig is covering. This clean plate you can later use to paint the ground back into the image (cf. “The Cinematic VR Field Guide”, 2017, p.32). And above this, it is recommended to continue to roll the camera on set until an unwanted object is out of the scene. Like this, you are able to comp the ‘clean’ part into the main action and remove the object. But this is only working if you shoot with a static camera (ibid. p.35).

After changing to a rectilinear format, you could actually work pretty close to a common VFX workflow, but a few considerations must be thought of when working with 360 degree footage. First of all previewing in VR is hard. On the one hand the ‘immersive’ preview is a problem, like already explained in the previously section because you cannot directly work in the output medium. So, in VFX you are not always enabled to adjust and view content in real time, but at least you always work on the ‘output image’. In VR you have to work on a equirectangular format that needs to be transferred in a rectilinear format to work on and still your final output image will be in a HMD (cf. “VFX for 360 VR, and why you are not prepared for it (Part 2)”, 2016). With this issue also client review is a challenge in comparison to a common 2D VFX workflow. You cannot work with common tools like, for instance, cineSync or Shotgun because they are predestined for 2D content. Moreover, VR files would be too huge to just stream them over cineSync. Consequently, getting feedback of the client is difficult because especially in VR you need precise notes and descriptions of what should happen or be seen in different parts of the image. And it is also hard to describe because there is no fixed direction like left or right like in a framed image. In addition, you cannot ensure that the client really sees things that you want him to see, except you lock the viewer’s orientation. Hence, there needs to be a solution how to communicate and exchange VR data for review. One possibility could be providing a tool for the client that allows reviewing and directly inserting notes in within a HMD by using motion controllers or defining definitions for the directions in VR (cf. ibid.). Another issue which always comes with VR is huge data files. The huge amount of data entails a lot of challenges of computing power and the whole pipeline. Not only that everything takes long time to transfer, back-up, compress or extract also the whole process is more susceptible for errors which can cause delays in the production workflow. Additionally, even most of the modern application support high resolutions still bugs, can occur when you load huge footage, such as for example 8K into an HD-minded workflow (cf. ibid.). Also, layering videos on top of each other can be a problem when working with huge amounts of data. In VFX it is integral to the workflow that one “expect[s] to be able to layer any media” (ibid.) on which one is working. But when dealing with huge resolutions, for example, 6K videos that are layered on top of each other can cause a software freeze up or even a crash (cf. ibid.). One solution to overcome this issue is to work with single ‘patches’ and after editing these, combining them into a full-frame. This approach does not work if a visual effect impacts the entire sphere and in this case, you need to use proxy files or commit to a lower resolution. In addition "big files might choke file servers" (ibid.). It can happen that if artists work directly off a SAN network[11] storage that this can suffer at certain points from "atypical slowdowns" (ibid.). Occurrences like this can reduce the system's response rates and lead to lost working days. Also, multitasking can be possibly lead to a freezing of the system. So, it is recommended to stick to one software throughout the production to avoid system crashes (cf. ibid.). Additionally, reliable tools might get unreliable. "Even heavily relied-on tools for platform-agnostic processes like fluid simulation, fur dynamics, particle behaviour, and various post-processes like radial blur, might hit processing thresholds you didn't know of when introduced to the high-resolution demands of VR production" (ibid.). And furthermore, with huge resolutions, you work with no playback in real-time because of the limitations in hardware, so you need to be aware that also the rendering tasks take a lot longer out of, for example, Nuke. Even for 'quick renders' where you want to check on some changes, you need to send them to a farm instead of just render them locally on your PC. This is another additional step that needs to be considered when working with VR. Also, at this stage of production, stereoscopic editing is an issue one needs to concern early enough. As stereo has not made it to the home entertainment market, many VFX companies have not necessarily upgraded their pipeline that suits stereo. One need to plan enough RnD when deciding to work with stereoscopic VR because it adds a new layer of complexity and also a dependence on tools that have not matured yet (cf. ibid.). If you decide to add interactivity to your 360 degree video, such as "invisible interactivity" for example, you need to be aware that the programming part for VFX has some challenges. It is often that events, that are triggered by the viewer, call for previous events that loop indefinitely. So, there is the need for creating 'loop-able' effects. That is something that is relatively uncommon in the traditional VFX workflow and rather used for computer-generated VR experiences. Still if you want to integrate such interactivity for your 360 degree video, you need to do research and find solutions for that (cf. ibid.).

All in all, it is a really time consuming workflow because of the high amount of data and the lacking computing power to manage all this data. Not only copying, rendering and playing something takes longer, also adjustments can take much longer as normally. Thus you are forced under certain circumstances to stick to simple design and rely on basic tools which are normally the last minute solutions in a 2D workflow (cf ibid.).

"Until both hardware and software go through extensive stress-tests and stronger systems arrive on the market, everyone working in post-production is underpowered when working in VR" (ibid.). So, one should be aware of all the challenges that come with diving into VR post-production and should not underestimate these. And with every production, there might emerge other breaking points that need to be considered. In their

11 Storage Area Network. A data storage network that stores large amount of data.

article ‘VFX for 360 VR, and why you are not prepared for it (Part 2)’, Outpost VFX states, “VR is today. So this is no time to moan and groan about our tools not being fit for the job. It is time to embrace the challenges and overcome them. Create new experiences which will hopefully be as inspiring to others as the ones that have inspired us in becoming VFX artists” (ibid.). Framestore’s Cattano mentions ”“increased content creation will spawn increased use, which will encourage new tools and improvements to be developed to solve some of the content creation and usability hurdles” – with VFX studios poised to do that development” (Failes, 2016).

There might be more advances in hard- and software and there are already some of the common VFX programs that prepare for extending these for VR. Such as for instance, the Foundry Nuke Cara VR plug-in or Adobe Premiere which also offers options for editing 360 degree content.

Editing in VR as well as Color Correction belong also to the postproduction process, but cannot be considered in the scope of this thesis. For color correction you can say that there is the possibility to color correct VR footage in the extension of the common program DaVinci Resolve. Also ideas of CC tools in VR, where it is possible to work directly in the output medium, are part of research and development and will also be mentioned in the following case study.

Audio and Distribution are also integrating into the workflow and will be considered in the following sections.

4.5 THE IMPORTANCE OF AUDIO

Audio plays an important role in VR. It is a key factor which has a huge impact on the sense of presence and can also be used as cue to lead the attention of the viewer through the VR experience. The team of the studio Tendril remarks “Do make use of powerful, 3D audio. It will add to the feeling of presence and spatial depth, which magnifies VR’s impact and immersive quality” (Robinson, 2016). In order to get a good VR experience environmental sound and spatial characteristics is a must. Hearing as a sense, gives a person sense of balance as well as is relevant to the vision of a person. Furthermore, people react more quickly to audio cues than to visual ones (cf. Jackson, 2015).

As VR allows the user to turn their head in any direction, it is necessary that the sound is transmitted as well as a 360 degree scene and it should match the listener’s point of view properly which demands head tracking in real time (cf. “The Cinematic VR Field Guide”, 2017, p.51). Virtual loudspeakers get possible through the use of so called HRFTs, which is the abbreviation for head-related transfer functions (cf. “Spatial Audio | Google VR”, 2016). These are responsible to provide spatial audio for head movement. ”When audio is played through HRTFs over headphones, the listener is fooled into thinking the sound is located at a particular point in 3D space” (ibid.).

The following cues can be captured within such an HRTF. When creating spatial sound, one must consider how people hear first. Main audio cues, that humans use to localize sound, are Interaural Time Differences (ITD), Interaural Level Differences (ILD) and spectral filtering done by our outer ears (cf. ibid.). ITDs consider the time arrival differences of a sound wave between a listener’s left and right eye. Depending on where the sound source is in space in relation to the listener this difference between both ears differ. The farther on a side the sound source is located, the larger is the time difference between both ears (cf. ibid.). ILD concerns differences in volume of a sound between both ears (cf. “The Cinematic VR Field Guide”, 2017, p.51). Spectral filtering considers sound frequencies that get bounced off in different ways by the outer ears. Like this the outer ears “modify sound’s frequencies in unique ways depending on the direction of sound” (“Spatial Audio | Google VR”, 2016). Besides these human sound hearing properties also the difference between direct sound and sound bouncing of surfaces, like for instance, walls must be considered when capturing spatial sound.

There are different audio formats such as ambisonic, binaural or Dolby Atmos, for example, that are capable of capturing spatial sound. “These sound formats record and emanate sound from where they actually occurred in the scene” (“The Cinematic VR Field Guide”, 2017, p.40 ff.). They are able to record sound in all directions and later cling these sounds to specific objects or visuals in the 360 degree video (cf. “Lesson: Shooting in 360-degrees”, n.d.). Depending on the situation, you can even project sound into 3D space to ensure that the 3D objects are considered in your spatial audio setup.

Despite different ways to approach capturing spatial sound, audio for VR is still a work in progress and “immersive audio is moving to the forefront of sound technologies” (Lalwani, 2016). So, there will be a lot more research and development in the area of immersive audio required in the next years, such as in other areas of VR. More information on spatial sound formats and how to mix it and synchronize it to create a proper immersive audio for 360 degree footage can be found in the ‘The Cinematic VR field Guide - A Guide to Best Practices for Shooting 360°’ of Jaunt Studios in chapter ‘Spatial Audio for Cinematic VR’ on page 51.

4.6 DISTRIBUTION

As already mentioned, there are new challenges to face with the amount of data VR requires. One of them is also distribution. And VR content needs to be distributed in order to become a successful medium. There are two primary methods how VR content gets distributed at the moment. One method is via desktop via web apps where the content is streamed and accessible through a web browser and the other is via mobile devices, where the apps are downloaded via an app store and installed (cf. Mahajan, 2016). The easier way to distribute VR content is via internet. There it is available for a wide mass and everyone with a modern browser that is webGl capable is enabled to watch 360 degree content directly inside the browser. But VR content via mobile phone which has an internet connection is also possible, as well as watching that content in a mobile HMD. “Because of the standardisation of both the video file format and the spherical distortion used for 360° recordings, distributing this kind of VR experience has very quickly become as simple as uploading it to YouTube or Facebook” (Lievendag, 2015). YouTube provides also a support for 360 degree videos as well as support for stereoscopic 3D content and offer complete upload instructions on their YouTube Help Center. Moreover, the web has an open publishing and streaming model which makes it easy for everybody to share and upload content (cf. Mahajan, 2016). Furthermore, web apps are immediately usable and also provide cloud-storage. But this distribution model is only really suitable for 360 degree content.

Besides the web browser distribution model, there is the app store-based distribution which also includes interactive VR experiences and games. For room-scale VR devices that do not work with the mobile phone, there is only the possibility of the app store distribution where one needs to download and install the app. Downloading takes time and these apps can be very large sometimes and it is unreasonable to demand downloading huge amounts of data every time they want to watch new VR content (cf. ibid.). As a developer, you need to submit a complete version of your app to Steam or Oculus for approval before being listed in the app store. That is a complicated way to go. In addition, it is still a problem that different VR content must be predestined for only Oculus or the Vive and there is no unified format you can distribute your experience. Like this, consumer having a Vive are not able to see your content if it is only forecasted for the Rift. That means, if you want to distribute your app to both devices you need to do two separated versions which are specialized on the needs of each device. Furthermore, the app landscape is a chaos at the moment. People are unsure about what they should search for, when they want to consume VR experiences because there is no unified platform for VR experiences, like YouTube is for videos (cf. Chow, 2016). Besides Oculus Store and Steam, there are only few other distribution platforms, more likely you will find an app where only one experience is provided.

“Another way to enable streaming is by creating a proprietary app that streams content within it” (Mahajan, 2016). This way can be compared to Flash and QuickTime being the original distributors of streamable video and rich content on the internet (cf. ibid.). Companies like High Fidelity and VRTV are working on a technology “which allows streaming of content within an app once it has been downloaded” (ibid.).

There likely will not be a single distribution strategy that is suitable for all forms of content. For high definition content, like games, a download and install via an app store will continue to make sense. For lightweight VR content, however, the streaming approach will allow VR content creators to easily publish and be assured that consumers will be able to quickly access and immerse themselves with minimal friction. That’s great for creators, consumers, and increasing engagement within the VR ecosystem (cf. ibid.).

There need to be ways to distribute the created content of a medium otherwise it will not have any success. “After all, no medium can truly take off if people can’t find a way to access it. And like many mediums, there won’t just be one platform that virtual reality will make its way to” (Huls, 2016). Besides the presented ways of distribution, there are also some companies that want to establish platforms especially for VR content and help to develop an infrastructure which makes it easier to distribute VR content. One of them is, for instance, Transport which is an independent VR network by Wevr. They want to provide a platform where they can create “a symbiotic relationship between artist and audience” (“Transport VR”, n.d.). “We think it’s vital to establish a sustainable business for this community so the medium can evolve and flourish” (ibid.).

Besides these distribution forms, there is also the possibility to distribute content in places where people get to in their all day lives, such as for example in a public area like a cinema. Or VR experiences could also debut in family entertainment centers or theme parks (cf. Robinson, 2017). That is a nice way to get the average consumer in contact with the high end-VR devices and show them what is possible with the medium VR when watching it in the best quality and experience it in the best way possible. Also marketing purposes could be a gateway to high-end VR experiences for consumers. And of course cheap VR solutions such as mobile VR, especially Google Cardboard are easy accessible and can lead to a first impression and contact with the medium.

5

CASE STUDY

VFX Companies Turning into VR

"I EXPECT THAT THE ABILITY TO SUPPORT AND CREATE CONTENT FOR IMMERSIVE EXPERIENCES WILL BECOME A COMMON TASK FOR VISUAL EFFECTS HOUSES IN THE RELATIVELY NEAR FUTURE."

– Michele Sciolette, Head of VFX Technology, Cinesite

Figure 94: Screenshot of the film 'HELP' (2015).

“At VFX studios worldwide, virtual reality has been a growing part of our pipeline for some time now” (Coulombe, 2016). There are a lot of Visual Effects houses that create meanwhile VR content besides VFX. As already mentioned in the section ‘VFX for VR’ above, there are quite a few reasons why VFX companies decided to also create VR content. A main reason is the understanding of 3D, but also the skillset of the artist like “working in key areas such as CG creation, compositing, tracking and virtual sets” (Failes, 2016) are reasons for VFX companies getting into VR. Audra Coulombe, Marketing Manager of The Molecule even states, “The reason why VFX companies in particular are in the thick of the VR revolution is that, in order to create a professional, high-quality virtual reality project, you need a visual effects team. Unlike traditional production, where you might have a VFX shot here or there, in VR production, every shot is a VFX shot” (Coulombe, 2016). And VFX artists also offer the needed technical skills for VR. “They are hit with complex issues all the time in visual effects that are all about getting the shot done, and VR is certainly no different” (Failes, 2016). VFX company Luma Pictures Managing Director Jay Lichtman says, “There are no entities better suited to harness and advance the VR medium than visual effects studios. We’re world builders who are now able to generate fully immersive and interactive worlds that VR allows for” (ibid.). As VR is quite applicable to the work of VFX companies, “it made business sense to enter the field, partly for fear of being left behind” (ibid.). The Mill’s Group Director of Emerging Technology Boo Wong recognizes, “Never before in our industry has it been so important to join concept development with technological expertise“ (ibid.). But for a lot of VFX companies it is also a chance to experiment with a new medium and they see it as incentive because of the unsolved issues and uncharted territories (cf. "VFX for 360 VR, and why you are not prepared for it (Part 1)", 2016). And there is excitement for VR. Patrick Osborne, the director of Google Spotlight Stories’ movie ‘Pearl’ mentions, „…It’s not often that you get to tread new territory…What could be more exciting than that?... Just get in there and make stuff. We creatives need to continually push each and the medium forward, so jump in and start exploring!" (Robinson, 2017). One important thing that should also be mentioned is that the VFX companies are not only focusing on 360 degree videos which are close to their common workflow, but also on Responsive VR with another workflow. The Third Floor, for example, also created an interactive VR experience to the movie ‘The Martian’ and ILM as well as PIXOMONDO provide a separated department which is only focusing in creating, researching and developing (interactive) VR experiences. “The VFX studios hitting VR hard right now include Industrial Light & Magic (with its ILMxLAB), The Mill, Digital Domain, Luma Pictures, Framestore, Mirada and MPC” (“VR Is A Key Component Of VFX's Future”, 2016).

As there is no existing study concerning VFX studios that also do VR at the moment, the approach was to take all major represented VFX houses of the last FMX (2016) as well as five other VFX studios where is known that they also deal with VR and compare them.

COMPANY	VR?	WHAT KIND OF VR?
3DEXCITE	yes	car visualization, customization
Animal Logic	(yes)	360° installation
Axis Animation	n/a	-
Cinesite	n/a	-
Digital Domain	yes	various 360° experiences,...
Disney	yes	Disney Movies VR, App
Double Negative	n/a	-
Dreamworks	yes	Dreamworks VR platform
Framestore	yes	various 360° experiences,...
Ilion Anim Studios	n/a	-
Illumination MacGuff	n/a	-
ILM	yes	Virtual Production (Star Wars), 360° experiences,...
Iloura	n/a	-
Image Engine	n/a	-
Luma Pictures	yes	VR experiences, 360° video
Mackevision	yes	product experiences, configurations
Method	n/a	-
Mikros Image	n/a	-
Mirada	yes	Apps, VR experiences, 360° video,...
MPC	yes	Virtual Production (Jungle Book)
New Deal Studios	yes	Live-action content for VR
Nordeus	n/a	-
Pixomondo	yes	Apps, Interactive VR, 360° content
Rise FX	n/a	-
Scanline VFX	n/a	-
The Mill	yes	VR experiences, 360° content
The Molecule	yes	360° video (e.g. VFX for the VR series ‘Invisible’)
The Third Floor	yes	Interactive VR experiences
Trixter	n/a	-
Weta Digital	yes	360° video experiences

Chart 2: Comparison of different VFX companies and if they are doing VR. The chart is based on own research. This information is supplied without liability and serves only as general overview.

The *chart 1* shows some VFX companies and if they are involved in VR at the moment or not. The companies where VR experiences or reviews of VR experiences are found, are marked with a ‘yes’. Companies, where nothing could be found on VR, are marked with a ‘n/a’.

5.1 GOOGLE SPOTLIGHT SORIES ‘HELP’

As case study the cinematic 360 degree VR live action film ‘HELP’ directed by Justin Lin, director of Fast and the Furious, is chosen. This immersive short film was created in collaboration between Google ATAP (Advanced Technologies and Projects), the production company Bullitt and the Visual Effects studio The Mill. It released 2015 as the first immersive live-action film in the course of Google Spotlight Stories. Google Spotlight Stories examines immersive storytelling through mobile 360, mobile VR- and room-scale-VR headsets and researches on new technologies and innovations to realize VR content (cf. ”Google Spotlight Stories”, n.d.). Before addressing a live action 360 degree video Google Spotlight Stories started with a CG-based (‘Buggy Night’, ‘Windy Day’) and hand-drawn (‘Duet’) approach to immersive storytelling (cf. Levy, 2014). Their last Spotlight Stories movie ‘Pearl’ by Patrick Osborne was even nominated for the best animated short category at the Academy Awards 2017 (cf. “The 89th Academy Awards | 2017”, 2017). Moreover, ATAP also plans to release what they call a Story Development Kit (SDK) that should be available for a large amount of filmmakers and storytellers. “With the SDK, an animator can build a story using familiar tools (e.g. Autodesk’s Maya) and set up interactive story in an intuitive way” (Bell, 2015), said Rachid El Guerrab, ATAP’s technical project lead for Spotlight Stories, in a statement. It should introduce a new ‘film language’ which shows creators how to think in 3D and 360 degrees and how to work with a free camera as well as viewer-based pacing (cf. ibid.).

‘HELP’ is chosen as case study in this thesis because it is a successful example for using classical VFX in 360 degree/VR space. ‘HELP’ also won a few awards so far, including two Gold Digital Craft Lions[12] for Digital Craft and Digital Craft: VR at the Cannes Lions Awards Show in 2016 (cf. “Google & The Mill’s ‘HELP’ Wins Two Gold Digital Craft Lions in Cannes”, 2016). In addition, the project provides a lot of information which is publicly accessible. Google ATAP’s content is furthermore predestined for mobile 360 degree and mobile VR headsets which make it accessible for everyone with a smartphone. „Your phone is the window into that world” (Roettgers, 2015) declares Regina Dugan, a member of ATAP group in an interview. ‘HELP’ is available on YouTube and Vimeo as well as for Android and Apple on the Google Spotlight Stories app via the Google Play or App Store.

12 Award in technological artistry. Cannes Lion Festival of Creativity.

All in all, it took 13 months and 81 people to create this monoscopic 360 degree movie. In The Mill's' 'Behind the scenes' – video, they state that they needed over 200 terabytes and rendered approximately 15.000.000 frames (cf. "The Mill, 2015). The story is about an alien attack in Los Angeles. After a meteor shower in Chinatown a woman discovers a small alien creature which grows during the film in size and malignity. During the movie this woman and a policeman, who wanted to help her, got chased by the growing alien through the streets of Chinatown, down into a metro station and finally close to the L.A. River Basin where the showdown takes place and the woman reveals the reason why the alien is so vicious (cf. "Creating the Alien Creature for Google ATAP 'HELP'", 2015). As The Mill states on their own website, 'HELP' is a "classic tale of explosions, aliens, heroines and heroes" ("Google Spotlight Stories – HELP",n.d.). Concerning that it is difficult to guide the viewers gaze in a 360 degree medium. Director Lin said during a Google I/O[13] session that "It's more of a shared narrative […]. When I go on set, it's very important, the lenses I choose, what I choose to frame or not frame and that's how I make my movies. And now I'm sharing that power with the viewer and it's actually very liberating" (Bell, 2015). But even if traditional storytelling ways do not work in 360 degrees, the makers of 'HELP' found ways to address the attention of the viewer. Lighting clues and effects throughout the movie create points of attention, as well as spatial sound and the storyline itself contribute to guide the user.

Figure 95: Opening shot from 'HELP' in an equirectangular format.

The goal of 'HELP' was to create a high quality 360 degree live action movie which also integrates computer graphical elements deploying cinematic quality VFX (cf. "Google Spotlight Stories – HELP",n.d.). "It was an interesting challenge because I don't think anybody has done it to the quality level that I think this piece has" ("HELP – fxguide", 2015), said Alex Vegh, the visual effects supervisor from the production company Bullit. There were a lot of technical challenges as well as the fact that story and cam movement had to work together. The RnD (Research and Development) phase was really important before shooting the movie. There were numerous tests and experiments concerning camera rig as well as stitching and pipeline issues. This project required a completely new creative language as well as the supporting technological systems (cf. "Google & The Mill's HELP Wins Two Gold Digital Craft Lions in Cannes", 2016).

13 Annual developer conference by Google.

There was a previs made in advance with one hero camera which could be watched in QuickTime and easily send via email. Later cubic spaces were used to screen the previs on tablets and smartphones. For that creation phase ATAP created a tool which made it possible to go for-backward and zoom in and out in a QuickTime and look at the latlong, so it was easier to prepare and get an idea of the shooting (cf. “HELP – fxguide”, 2015).

First approaches concerning camera started with 2K SDI Cams and C mount lenses, for example, like from the company Fujinon. The development team had a 20 inches big sphere with 16 cams on it and experimented with the number of cams. A GoPro rig was not considered because it could not deliver the desired quality. That is why they ended up with a custom build array of 4 RED cams with fisheye lenses and shooting in 6K. Through 6K the desired quality and resolution in 360 degree could be provided. Even if the end medium is a smartphone, which actually does not require such a high resolution, you only see a small area of the whole image in 360 degree space and therefore the footage still must provide a high resolution. Resolution was also an issue which decided about the choice of camera. The RED was chosen over the ARRI because it allocates the highest resolution for a shoot at night and with 30 frames per second. The biggest problem to be aware, of which is also mentioned in chapter four, is that the parallax of far away and near objects differs if there are two several cams which have not the same nodal point. There were different approaches to solve parallax issue. The first one was an optical approach through trying to get the cameras as nodal as possible to be able to get the action closer to the cameras. The second approach was a software-derived one and contains trying to gain all depth information from all of the cameras and then use the pixels to project that onto geometry (cf. “HELP – fxguide”, 2015). In a conversation with Patrick Heinen, one of the 2D artists working on the ‘HELP’, he also talked about the approach to take one hero camera, bringing all the information into 3D space and then filming it from that hero camera (cf. conversation with P. Heinen, 2017).

For the rig, a cart system was considered at the beginning. But there was a need of freedom in moving as well as the condition that the system has to work along with long sequences which no Motion Control - unit could comply. “So we wound up using a Spider-cam cable-cam, three different companies to do cable operated systems - to try and keep us in a few passes as possible so we didn’t have to repeatable movement” (“HELP – fxguide”, 2015), said VFX supervisor Vegh to fxguide in one of their podcasts. In the end, four cameras for that rig were chosen because fewer cameras provide less seems and this amount was good enough to protect the desired resolution. The cameras were rotated edgeways on the rig so that they got 180 degree vertical and approximately 120 degree horizontal. Like this, they got full 360 degree vertically. So there is more overlap concerning the case when a character crosses the ‘frame’ which is a critical moment because effects like ‘ghost’-effects can occur which is explained in the previous chapters.

Figure 96: Camera rig of the ‘HELP’.

Figure 97: Camera rig, 3D modeled.

Figure 98: Camera rig in shooting.

Figure 99: Camera rig.

Due to that, the four cameras needed a field of view of 180 degrees, for correct amount of overlap there were different lenses tested before shooting. It required a lot of research to find the appropriate lenses because it was important that all parts of the image were nearly sharp to afterwards blend them into each other. Amongst others, a Canon Zoom lens got chosen because it provided nearly sharpness across the entire lens. Even if they were photography lenses, the technical team of ‘HELP’ decided that these were the best option for their purposes (cf. “HELP – fxguide”, 2015). As all cameras are slightly different, a perfect calibration for them was needed. So, there was a software developed that measures the lenses very precisely and so distortion and chromatic aberration can be prevented (cf. The Mill, 2015, 00:01:09 ff.).

Another tool which was developed was the ‘Mill Stitch’, consisting of hard- and software for real time live stitching on set by The Mill. So, as review on set there was, besides four monitors with the original fish eye lenses images, one monitor where these four cameras got dewarped and stitched in real time. Furthermore, it was possible to adjust lenses with a joystick which enables to zoom in or out in the 360 latlong. Also the previs could be layered on the live shoot so that it was possible to check on characters interactions. As well as a wireless monitor was used on set as a virtual camera which gave the director the opportunity to stage actors and work out the framing (cf. "HELP – fxguide", 2015). ""The amount of data was huge," explained Bullitt CEO Todd Makurath, adding that it required a 48 terabyte RAID setup on set" (Roettgers, 2015). There was also an app created for viewing dailies[14] where material could be reviewed on a tablet after shooting (cf. "Google Spotlight Stories – HELP, n.d.).

Figure 100: Camera rig and stitching overlap of the cameras.

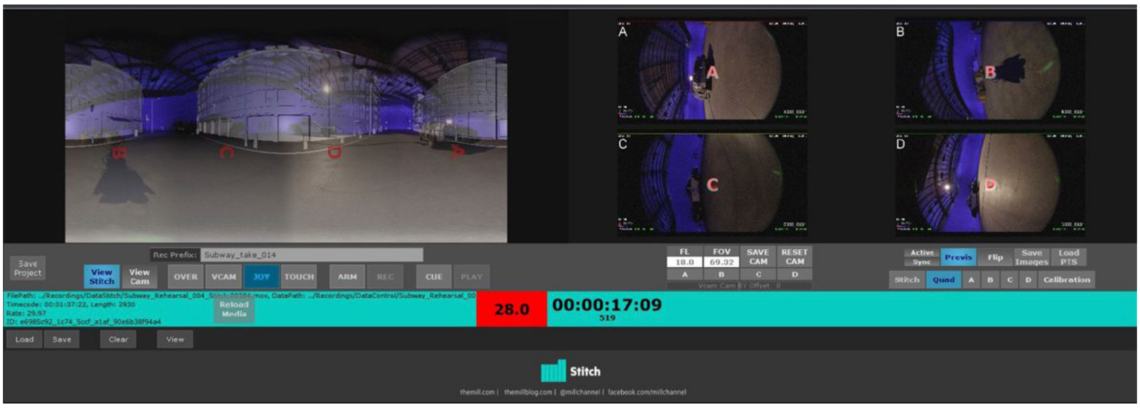


Figure 101: The Mill Stitch, no.1.

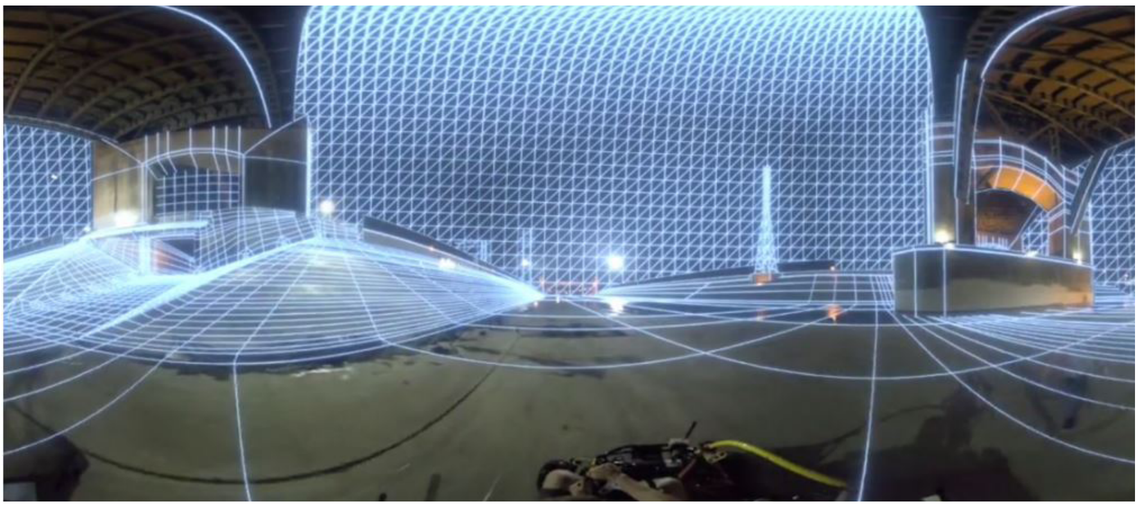


Figure 102: The Mill Stitch, no. 2.

14 Any raw footage which you check every day to see the progress in a film production.

Working on set requires also another approach as the traditional way. By viewing in all directions the light set ups as well as production design needed to be considered thoroughly beforehand and required creative solutions. And light is also a problem when a lens flare is caused in one of the lenses, but not in another so that had to be figured out quite well. To overcome the problem of seeing light set ups in the whole set, practical lighting has been chosen in combination with automated lighting systems to lighten the scene. Also, production design was challenging because of the used spider-cam that hung on the ceiling and needed to go everywhere on set (cf. “HELP – fxguide”, 2015.

In postproduction, the first step was to consider how the main CG character, the alien, should look like and how the transition from cute and small to monstrous and aggressive should be made. On the base of the original concepts from Justin Lin it got decided how the small creature should look like and upon this base the transitions were developed (cf. “Creating the Alien Creature for Google ATAP ‘HELP”,2015). “Crocodile, elephant and rhino skin, as well as bearded dragons, were referenced to get the right balance” (ibid.).

Figure 103: Concept art of the alien.

Moreover, a glow effect was added to the creature throughout its transitions to show that it takes effort to transform. Also scale became a challenge because the “creature grew from about half a foot to 200 feet tall” (ibid.). To enable smooth transformations, the alien needed the same mesh, which is blendable, as well as a blendable skeleton. “Lead character artist Majid Esmaeili shares, “One of the more difficult parts of designing the character’s evolution was to make the spikes that appear in Phase 2 and grow to more than 4,000 spikes in Phase 5” (ibid.). Besides the character building there was also a huge amount of assets that had to be built in CG and afterwards integrated in the live-action footage.

Figure 104: Alien in different stages.

The difficulty for VFX was first of all handling the huge amount of data. There were 6K raw files from four cameras. So the first challenge was to manage this data and then stitching the footage. “During post-production, a more refined version of ‘Mill Stitch’ was used in tandem with several other proprietary software tools to rebuild a seamless drama combining live-action and vast CG environments” (“Google & The Mill’s HELP Wins Two Gold Digital Craft Lions in Cannes”, 2016).

But besides the numerous data, also reviewing took longer because you have to watch the scenes in all directions again and again. Another issue is the fact that shots are now difficult to share such as it is common in Visual Effects because of the format and the long sequences that come often along with 360 degree films (cf. conversation with P. Heinen, 2017). And dealing with latlong in compositing as well as in color timing or with motion blur can cause problems for artists because pixels on the down and button do not match. Also the captured resolution differs on bottom and top. All in all, there must been a detailed work because for set extensions, CG as well as digital and practical lighting, a higher resolution as common was used. Concerning the environments a full CG approach was made to allow an easier blending between different cameras and enable a better amount of control to manipulate the environment (cf. Solomon, 2015).

VFX supervisor of The Mill, Gawain Liddiard, tells in the ‘Behind the scenes’ - video that “the scale of the FX and the number of effects would have made the film a huge challenge even if it had been a traditional format, without a 360 perspective” (Solomon, 2015). There are a lot of events happening, the whole scale changes during the movie and the camera moves through long continuous shots.

Concerning Color Grading, Colorist Gregory Reese states that it is conceptually quite similar to traditional projects, but you are not able to watch your work directly in the end medium (cf. “Gregory Reese on Colour Grading 360 Film Google ATAP ‘HELP’”, 2015). But there are tools in development which will allow live grading with headset and traditional monitor (cf. ibid). “It might challenge your muscle memory as a colorist, as you can’t see the controls, but it completely removes the guesswork of how things should look when the film goes out to the masses” (ibid.), said Reese. There was a close cooperation between colorist and comp and CG leads. Some things were adjusted in CG, some in comp and some in grading. During the post production process it was figured out what is the best solution for technical as well as creative decisions. So, communication was very important. There were no vignettes or gradients added in grading to preserve the immersion of the movie.The film includes 3D sound. A stereo mix was put in a binaural space and provided spatial sound because the people, characters and CG elements were tracked in 3D space and then the sound was projected individually in the environment (cf. “HELP – fxguide”, 2015).

Of course ‘HELP’ contributes to the discussion whether it is VR or not. Like in the article ‘How Google and Justin Lin Are Reinventing Movies For Mobile’, „Everyone involved in Spotlight Stories was quick to point out that there are notable differences between stories like “Help” and VR” (Roettgers, 2015). But still it is a kind of form in VR and as defined in the beginning, it is definitely one form of Virtual Reality. And until the terminology is not properly defined yet, mobile VR and 360 degree videos will be the medium to reach wider masses. “360 video offers a relatively cheap bridge to the new medium” (Smith, 2015). And brands and companies, such as for example Facebook, use 360 degree video because it is possible for them “to leverage their massive user bases on platforms that everyone is already using” (“The Cinematic VR Field Guide”, 2017, p.11).

There were also some comments concerning the suspension of disbelief on ‘HELP’. Brent Rose, for example, mentions that the short is “extremely impressive” (Rose, 2015) and “good taste of what movies could become once VR becomes more ubiquitous” (ibid.). But that ‘HELP’ also brings some issues with the suspension of disbelief. Being chased by an alien, the camera must be shaky instead of using smooth dolly-motion which helps the user to follow the action and reduce motion sickness but also breaks the ‘presence’ and with it the reality of the situation (cf. ibid.). Another thing which makes the user doubt in reality is that he is in the middle of the story, but has no character and acts passive while being hunted by the alien. That also tends to break the illusion of “really being there” (ibid.). Nevertheless the short was quite impressive for its time and got its appreciation through the prices it has won. Rose mentions beside the comments on the suspension of disbelief, “All that isn’t to say that Help isn’t impressive. It really, really is.” And Gawain Liddiard said on their winning in Cannes 2016 “‘HELP’ is a landmark film; a beacon of what can be achieved in new media formats” (“Google & The Mill’s HELP Wins Two Gold Digital Craft Lions in Cannes”, 2016). And in an interview after the ‘HELP’ shooting, director Justin Lin admits that: “(…) this exceeded my expectations. As a storyteller myself, I can’t wait to have another opportunity” (Levy, 2014). And as 360 degree content as well as VR are still an evolving area, there will be a lot more content in the next years.

Figure 105: Assets for 'HELP'.

Figure 106: Screenshot from 'HELP', no.1.

Figure 107: Screenshot from 'HELP', no.2.

Figure 108: Screenshot from 'HELP', no.3

Figure 109: Screenshot from 'HELP', no.4.

6

ISSUES

“FOR VR AS AN INDUSTRY TO MAKE PROGRESS PEOPLE WHO MAKE CONTENT HAVE TO MAKE MONEY“

– Shuhei Yoshid,
President of Sony Interactive Entertainment

Figure 110: Audi VR Experience. Users need to try VR before they can understand its features.

In this chapter remarkable issues concerning VR as medium are highlighted. An extensive analysis of issues and problems would exceed the scope of this thesis so there will be just some main issues chosen and presented.

The main issues VR faces at the moment are on the one hand technological and on the other hand marketing challenges. Moreover there is no unified standardization concerning VR. "Virtual Reality as medium is still in its infancy" (Kopstein, 2016) and the technology is still immature (cf. Bastian, 2016). One main issue is the lack of standardization in naming conventions, as well as in content creation, formats or workflows. Nicholas Fortugno, CCO and Co-Founder of the gaming and VR designer firm Playmatics states, "I think that we still haven't found the basic vocabulary of virtual reality and that's the challenge we have as an industry" (Kariuki, 2016). And also, the fact that there are still apps or experiences that only work for either a HTC Vive or an Oculus Rift needs to be solved in the future. There has to be a unified device driver structure. CEO of the VFX company the Molecule Chris Healer says, "so that it's just VR, not Oculus VR or Vive VR" (Marchant, 2016).

The technology is still in development and there are improvements needed to get VR to the mass market. The wires are definitely a problem which should be solved to provide an immersive experience with a sense of presence. Also HMDs need to get improved concerning graphical processing, latency and resolution. Max Alexander said "Within a couple of years, we'll have 4K or even 12K resolution that will give incredible visual fidelity" (Alexander, 2016). So a future issue will be as well the handling of huge amounts of data. Also improvement of tracking and input devices is needed for gesture capturing and facial expressions as already described in the chapter concerning tools with telecommunication. Furthermore, eye-tracking technology could also improve non-verbal social interaction and also graphics through foveated rendering, guarantee secure authentication and provide a more intuitive user input (cf. Madott, 2016). And there are still some limitations in tactile and spatial awareness in VR. Even if we can interact and move around objects in Responsive VR we are still not really able to feel them except there is an object which has the same shape and characteristics as the seen object in VR. There is the question if we need also temperature, humidity and the texture simulated of the object and how this could be achieved to provide a better sense of presence (cf. Alexander, 2016).

Another issue is motion sickness that can occur if user experience VR and the auditory canal is not in unison with the visual system. This is a common issue occurring at Cinematic VR experiences because there you are not able to physically move in the virtual environment and you got moved by the camera of the creators. In room-scale VR which provides real-time tracking there is no disconnection between the physical and virtual actions and therefore motion sickness is not that prevalent (cf. "The Cinematic VR

Field Guide", 2017, p.24 f.). But for instance VR experiences which put you out of your normal physical forces, such as riding in a spaceship, are prone to make people sick (cf. ibid. p.25).

As already mentioned in the case study 'HELP', main problems that occur in post-production of 360 degree VR content are handling a large amounts of data as well as stitching all the footage and the camera alignment. Also rendering and compositing in an equirectangular format proves as a challenge (cf. Thacker, 2015). In addition, stereoscopic 360 degree footage is even harder to process because the amount of cameras that must be stitched and the amount of data is also increased. Also, reviewing is hard because you cannot yet do compositing in a VR headset. Other issues that the VFX industry has to face in the future are real-time, lightfield technology, as well as adapting to new standards. "Every six months there will be a new group of them [HMDs] that will be better and more powerful with higher resolution" (Marchant, 2016). So the VFX companies need to adapt the content and workflow to new prototypes and develop new ideas.

Another huge issue is that there is no user base or specified target group for Virtual Reality. People who are now using VR and are aware of the technology are "early adopters and a growing community" (Cone, 2015). Even after almost two years public testing of the Oculus Rift, Nabeel Hyatt, venture partner at Oculus investor Spark Capital, said that the Rift is "still not something my mother would know about if we hadn't invested. Basically there's no user base" (Hof, 2015). Gamers are more likely to get into VR because for games VR promises an intense interactivity and there are also quite a few VR games on the market (e.g. 'Minecraft' or 'EVE Valkyrie') (cf. Lee, J. 2016). So gamers as target group are easier to get excited for the VR technology even though that does not mean that all convinced gamers are in the possession of a VR headset right now (cf. Matthews, 2016). But among the wide mass a lot of people do not even know what VR is or have misconceptions about it. Maureen Fan, the CEO and Co-founder of Baobab Studios mentions that one of the biggest misconceptions concerning VR is that "VR is just for gamers" (Situ, 2016). So VR must also reach non-gamers to gain consumers. Another huge problem is that the users do not know the differences between 360 degree VR, Interactive VR or VR games. As it was also a definition problem in chapter '3.1 Controversy about the Terminology', it is difficult to solve this problem until there is no defined terminology. Darshan Shankar, CEO and Founder of the xxx company Bigscreen, mentions "VR makes people sick" (ibid.) as misconception besides the 'gamer-statement'. And these statements come with another issue which is that VR as a medium needs to be tried to be understood. And also the different types of VR need to be tried before it is possible to understand what every single form of VR feels like. There is a difference between watching a 360 degree video in a Cardboard and playing an interactive VR experience in a HTC Vive. "You have to try VR to really understand it, and see its immense potential to transform the way we play, interact, learn and create…

The possibilities are endless" (Robinson, 2017) says Resh Sidhu from Framestore VR studio. Moreover, it is known as a medium which works as single-person experience and the HMDs still look a bit bulky and weird on the head. Furthermore, they block the users' views from their surroundings which make some users feel uncomfortable. So the social acceptance is not present for VR yet.

In addition, only few people own the hardware to experience VR at the moment. One reason for that is that most computers cannot yet face the needs of VR. According to the xx company Nvidia "less than 1% of the PCs expected to be in use globally in 2016 will be powerful enough to run the best virtual reality technology" ("'Less than 1%' of PCs can run virtual reality - BBC News", 2016).

Another issue concerning the households of the consumer is that besides there is no PC that can run the VR applications there is also a space problem. In most people's homes there is no dedicated room for VR. Take-Two CEO Strauss Zelnick says to this issue, "We don't have something where you stand in a big open space and hold two controllers with something on your head--and not crash into the coffee table" (Makuch, 2016). And some of the room-scale VR systems really need space to enjoy the experience.

And also the price of VR technology is a main issue because HMDs are expensive and if you also need to buy a new powerful computer that is capable of dealing with the VR technology the price will be quite over 2000$ (cf. ibid.). Zelnick says "It's way too expensive right now. There is no market for a $2000 entertainment device that requires you to dedicate a room to the activity" (ibid.).

The study '2016 Augmented and Virtual Reality Survey Report – Industry insights into the future of AR/VR' from the global law company Perkins Coie LLP and the organization addressing the AR and VR community Upload concerns issues that still prevent VR and AR to get adopted by the masses and challenges that come with these mediums. One of their questions they investigated was "What is the biggest obstacle to mass adoption of VR technology?" (Perkins Coie LLP, Upload, 2016, p.7).

Figure 111: Question: 'What is the biggest obstacle to mass adoption of VR technology?'

All in all you can see in *figure 111* that in the statistic the biggest obstacles concerning mass adoption of VR technology are user experience, cost and social acceptance; the issues that have been described in the previous section (cf. ibid. p.7). But also the not fully-matured content that is offered at the moment and the lack of a unified distribution platform are reasons why VR still is not yet a mass adopted medium. In the same study the biggest challenge of VR/AR as a whole are addressed (cf. ibid. p.9).

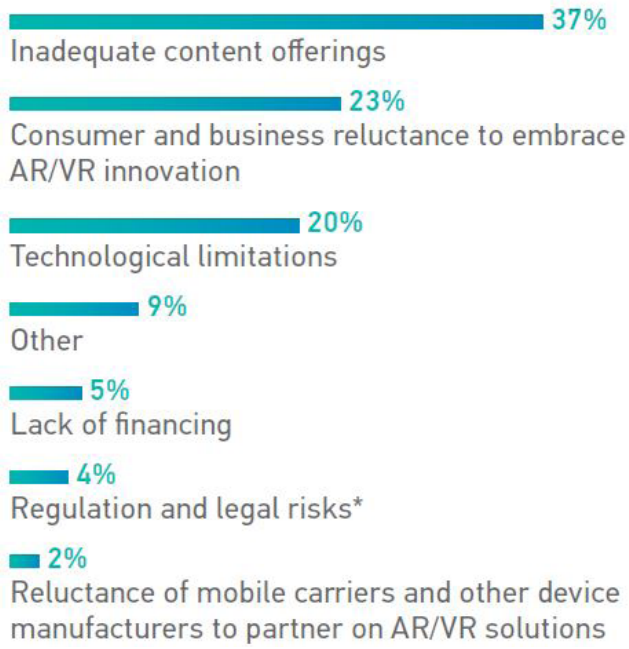


Figure 112: Question: 'What is the biggest challenge facing the AR(VR industry as a whole?'

As you can see a main challenge is the inadequate content offering. At the moment there is just too much content which is not in a good quality because the whole VR industry just begins to evolve and so do ways to present stories in VR, as well as the technology needs to improve (cf. ibid.). So, one of the main challenges is definitely the offering of better and adequate content. The other top challenges concern the reluctance of consumer and business to embrace the VR/AR innovation and the technological limitations VR or AR have (cf. ibid.). Some of the technological issues that still have to be overcome are presented in the previously sections and also the issues why VR is not yet accepted by the main society is explained above. Moreover there is no clear funding or business model developed as well as ethical and medical risks are not yet considered.

There are still issues that need to be dealt with, until VR will have the chance to become a fully adopted mass medium. And there will be way more issues following because everything in the area of VR resides in change and development. Therefore upcoming solutions and new challenges that will emerge in the future still need to be monitored.

7

FUTURE

THE BEST WAY TO PREDICT THE FUTURE
IS TO CREATE IT.

– Alan Kay (cf. Jerald, 2016, p.485)

Figure 113: Picture of a matrix.

Issues are closely connected to the future because a lot of challenges now will most probably improve and contribute to define the forthcoming developments. For example, there might be technical improvements such as new generations of HMDs and tracking methods. It is probable that the development will go towards finding unified terminologies and standardization of technique and equipment as well as more and more content creation and new applications that evolve. VR has definitely potential for the future but there are still some steps missing until VR becomes an accepted main stream medium.

The state of VR at the moment can be described through Gartner's Hype Cycle.

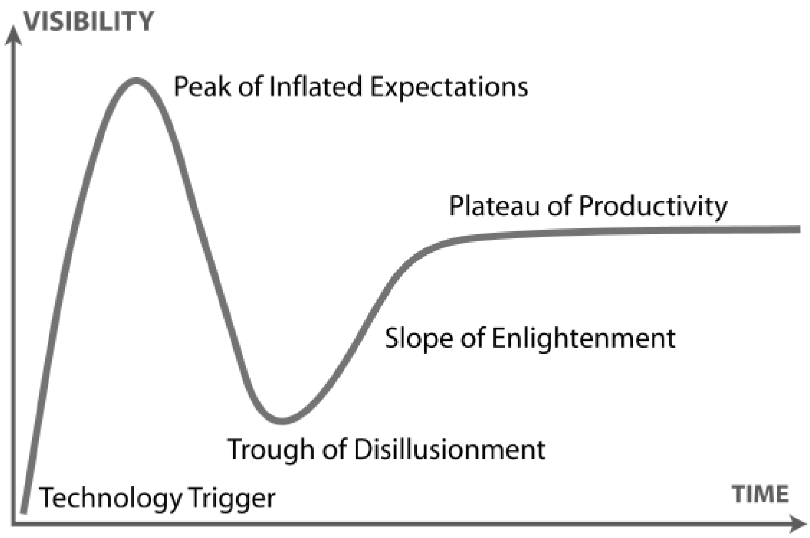


Figure 114: Gartner Hype Cycle.

The Gartner Group recognized that new technologies follow a certain pattern in their development and that is what they call a 'Gartner Hype Cycle'. It consists of five main stages, that can be seen in the *figure 114* and shows the development as well as the expectations and visibility of technology in each stage (cf. Sherman, & Craig, 2003, p. 439). It can therefore be used as a tool to compare VR with other technologies. You can see how technology progressed from an idea to a concept until it ends in a practical tool for everyday and mainstream adoption. Gartner predicts different emerging technologies every year. The Gartner Hype Cycle from July 2016 (cf. *figure 115*, next page) can be taken as basis to describe the state of VR.

Gartner predicts that VR still needs five to ten years until it can manage to become a mainstream technology. Three phases VR has already passed. The first one was the 'Technology Trigger-phase'. In case of VR the invention of Sutherlands first HMD (1968) or the definition of the term 'Virtual Reality' by Jaron Lanier (1989) can be seen as trigger occasion. At that time VR was only in its beginning and there were only few products and developments in this area. After that the research in the VR area increased and there were some successful stories but also failures. This phase describes the 'Peak of Inflated Expectations'. You can say, that between the years 1992 and 1995 there was high visibility of VR and also high expectations grew in that time. Following this part of the Hype Cycle the phase of "Trough of Disillusionment' leads to a downfall of the technology caused by disappointment and too high expectations. Therefore the interest in VR ceased, the media interest went back and a lot of companies had to drop out of the VR business because it was hard to remain in the business. After that the invention of the World Wide Web and other technologies left VR behind and far away from consumer visibility. That was approximately during 1995 and 1998. Concerning the state where VR stands right now you can realize that VR is situated at the beginning of the 'Slope of Enlightenment' phase. This phase consists of new adopters such as for example Palmer Luckey, the inventor of the Oculus Rift and a new flourishing community that gets interested in VR again. There are improvements and developments as well as the benefit of the medium can be understood better. Moreover second- and third generation products get released by technology providers. (cf. "Hype Cycle Research Methodology | Gartner Inc.", n.d.). If VR manages getting over this phase of development and the numbers of technology adopters rise, VR can make it to the last stage which is 'Plateau of Productivity'. At this stage the surviving technology can be accepted by the consumers and is able to settle down to a level of use, dependent on market size. There will be still advances and new generations of products and the technology will get into mainstream adoption (cf. Sherman, & Craig, 2003, p. 439).

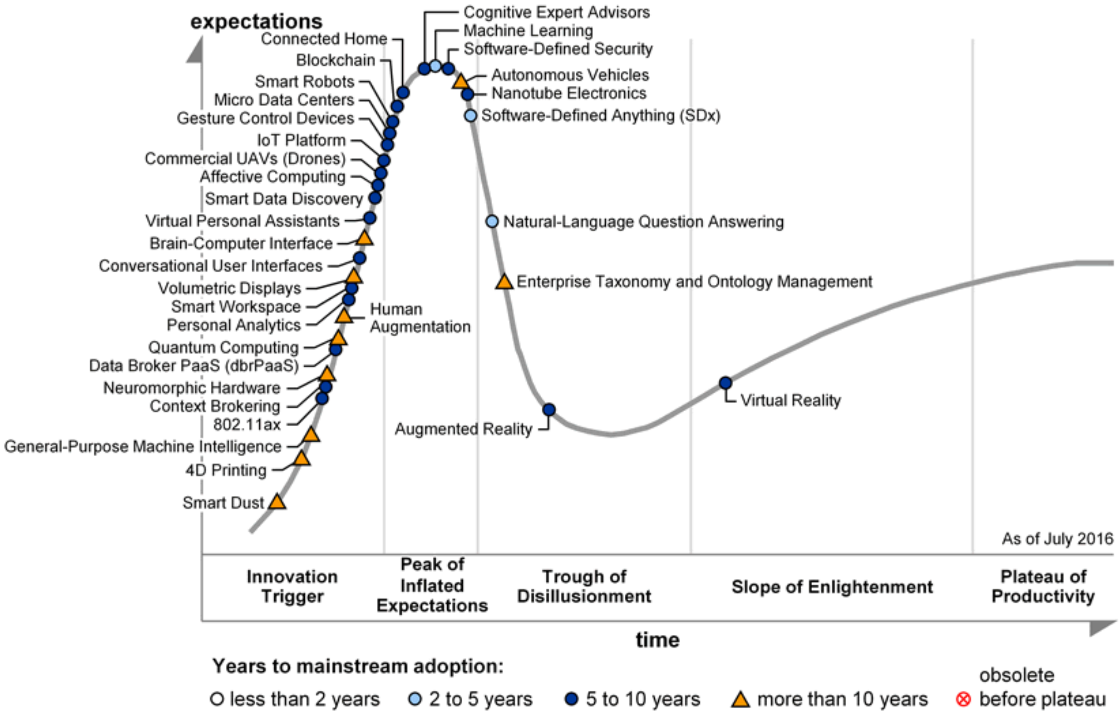


Figure 115: Gartner Hype Cycle July 2016.

Whether VR manages the step to mass adoption is unsure but the ecosystem of VR flourishes. The following *figure 116* shows the 'VR Industry Landscape' of 2017 created by The VR Fund. The graphic shows plenty of companies and start-ups that got involved in the new medium VR in all different areas such as applications, tools or infrastructure in the past three years.

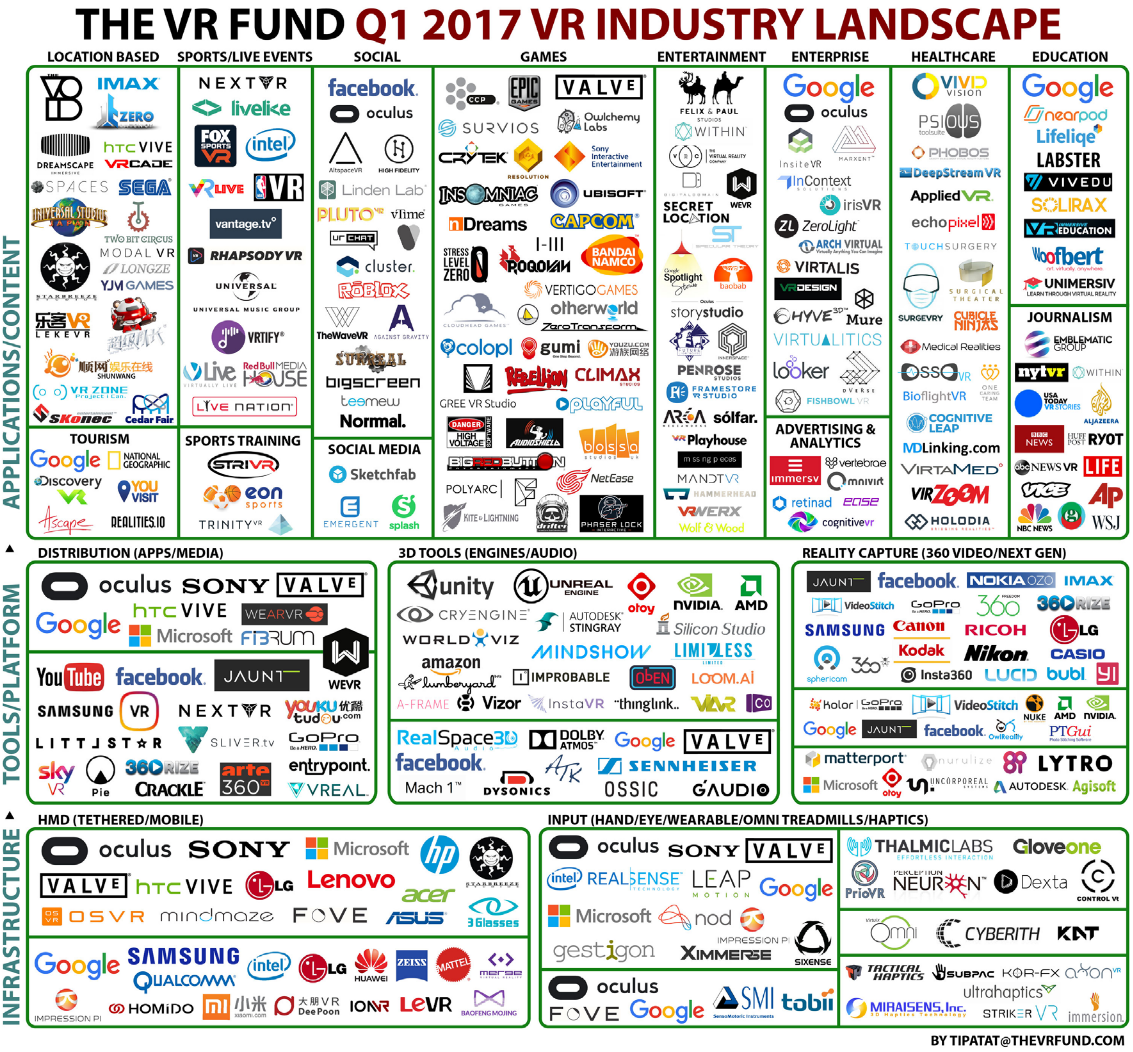


Figure 116: VR Fund Industry: VR Landscape Q1, 2017.

According to a study from February 2017 the "world's leading provider of market intelligence covering the global markets for free-to-play games, digital console, mobile, PC, streaming media, eSports, and virtual reality" ("Games data and market research - About Us", n.d.) SuperData released, the worldwide revenue of Virtual Reality in 2020 will be almost 38 billion dollar (cf. "SuperData and partners announce VR Data Network", 2016).

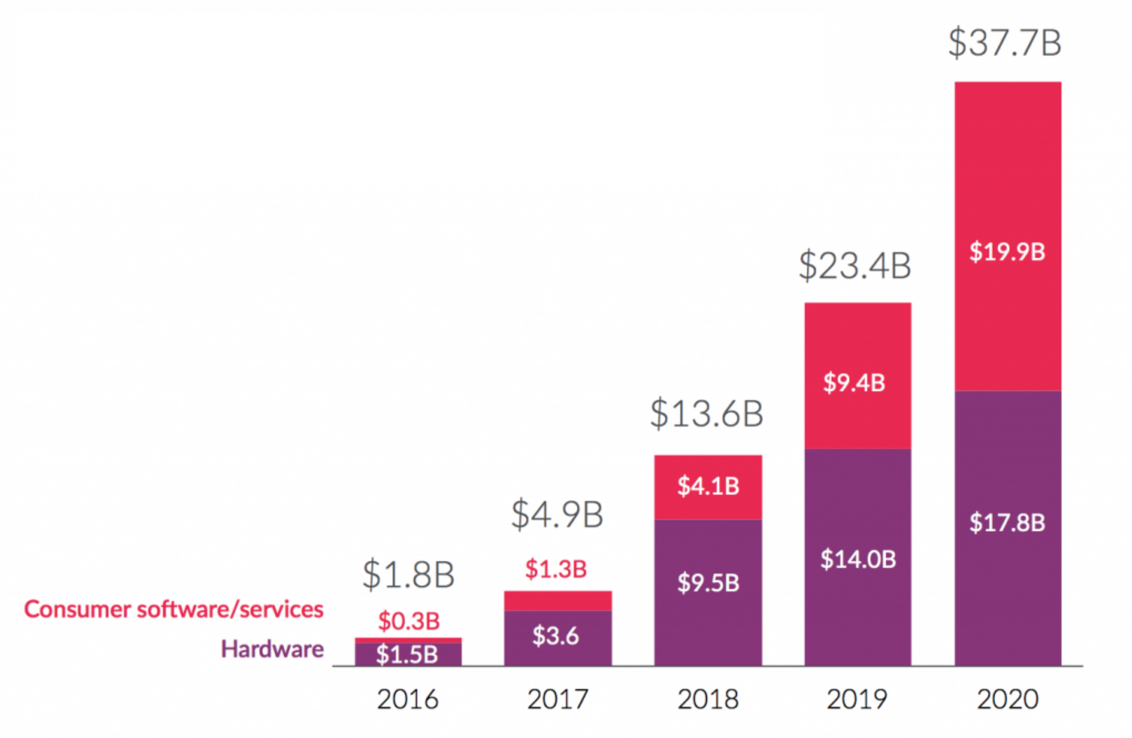


Figure 117: Worldwide Virtual Reality revenue by segment.

“There’s no doubt the virtual reality and augmented reality market will be an explosive new medium, hitting $37.7B in 2020” (ibid.), stated Stephanie Llamas, the head of research of SuperData. Moreover, she said that “VR needs to begin the process of measurement and validation” (ibid.). This is the reason why SuperData and some partners decided to launch Data Network, a network that allows Virtual Reality companies “to collaborate on insight projects and sizing efforts to verify the scope and trajectory of the market” (ibid.). “The VR industry is changing extremely rapidly, so it’s more important than ever to have reliable, accurate data we can use to make decisions” (ibid.), mentioned Julien Dulioust, who is senior monetization director at CCP Games, a leading VR and games publisher company which is also founding partner of the Data Network. With the foundation of a VR Data Network the shared insights which are provided should “push the industry toward general adoption and grow it into a healthy ecosystem for industry stakeholders” (ibid.).

Besides, end of 2016 the creation of the non-profit-organization Global Virtual Reality Association (GVRA) was announced. This group has made it a task to help VR as a medium to develop and broaden its opportunities and global potential (cf. "Global Virtual Reality Association", n.d.). It consists of main headset manufacture companies such as Google, HTC, Facebook’s Oculus, Samsung, Sony Interactive Entertainment and StarVR Corp (cf. ibid.). This association wants to create awareness of this medium’s growth and push the development and deploying of the technology forward. Through international dialogue and collaboration the GVRA wants to “ensure the continued growth of the VR ecosystem worldwide” (ibid.). “The rapid growth of the virtual reality industry presents many challenges as well as opportunities. It is important that we set a clear precedent for best practices and create a solid foundation from which we can build meaningful progress" (ibid.), said Tae-Yong Kim the Vice President of Mobile Communications Business at Samsung Electronics.

A lot of people predict that cardboards or other smartphone compatible VR headsets will function as 'gateway drug' (cf. Dotson, 2016) to the medium VR. Again SuperData predicts that "light mobile virtual reality devices […] will drive the market at first with an audience of 27.1 million" (Gaudiosi, 2016). As 360 degree content is at the moment the easiest way to distribute VR content and which is affordable and available, consequently it is often consumer's first VR experience. "So, for most purposes, 360° video is currently the only way to easily present high quality content to the more casual VR early adopters that are willing to buy inexpensive mobile VR hardware to give it a try" (Lievendag, 2015). As 360 degree content might probably be the first contact from consumers to VR one must work on crafting more engaging and appealing content. In addition 360 degree content has the advantage that it can also be shared via providing the YouTube link to the experience, for example. Thus, "content is the big question, and the biggest challenge of all, remains how to create content that will continue to entice and engage people for years to come" (O'Brien, 2016). As the technology gets better and HMDs get cheaper it will be easier to bring also room-scale VR to the people. And when they already watched good content with a mobile HMD they might be more willing to also adapt one of the room-scale headsets. Sherman and Craig write in their book 'Understanding Virtual Reality': "It is just a matter of time before such systems and much more sophisticated systems are available to almost everyone regardless of their computer skills and budget" (Sherman, & Craig, 2003, p. 457). It is now the challenge of VR content creator, developer and researcher to provide good quality content, appropriate technology, pleasant user interfaces and interaction techniques to support the progress of VR as a medium. Moreover, Craig and Sherman write "What we are developing now is the future. We need to be prepared for a future built on what we are doing today" (ibid. p. 457).

"Much like, VFX, Virtual Reality will continue to quickly break new ground with each generation requiring developers and their managers to be especially nimble and able to quickly pivot" (Stokes, 2016). Concerning VFX and VR the future also depends on the adoption of consumers. As discussed in the main parts of this thesis VR suits to some extent the VFX workflow. There are few VFX companies that see VR as a possibility of being part of an emerging technology. They contribute to the development of the medium as well as other companies in the area of gaming or pure Virtual Reality start-ups do. Some also join the development out of business reasons or out of fear of being left behind (cf. Failes, 2016). As YouTube supports 360 degree content VFX companies, which create 360 degree videos, they have good possibilities to distribute their contents. Like already mentioned in the previous chapter, Michele Sciolette, Head of VFX Technology of Cinesite, expects "the ability to support and create content for immersive experiences will become a common task for visual effects houses in the relatively near future“ (Edwards, 2015). But there are also some VFX studios that do not get involved in VR and are skeptical if VR is managing to get to a mainstream adoption. Concerning storytelling in VR, Pixar Co-Founder Ed Catmull expresses his concerns about VR storytelling. “It’s not storytelling. People have been trying to do [virtual reality] storytelling for 40 years. They haven’t succeeded. Why is that? Because we know that if they succeed then people would jump on it” (Dredge, 2015). He opines that VR as technology is not a “creative dead-end” (ibid.), but for narrative storytelling it may be the wrong medium. He says, “We have a whole industry which is gigantic: games. Games is very successful. It’s its own art form though, and it’s not the same as a linear narrative” (ibid.). And also Jeremy Bailenson, Head of the Standford University VR Lab, refers to the high expectations of VR with “Most things don’t work in VR. If you show me 20 ideas, I’ll say 19 of them would be better in another medium. […] I think VR is best for special, intense experiences… things that are expensive, dangerous, counterproductive, or impossible” (O’Brien, 2016). Therefore it could be that VR will only be serving a small niche and will not be a successful business for VFX studios besides their common VFX business. But on the other hand it could also be thinkable that games, VR and VFX technology merge and there will be only one workflow that includes all of them. Additionally, it really depends in which sectors VR will find its sense of existing and where VR proves to be a successful medium. Like described in chapter three, there are three main connections of VR and VFX and how these will develop in future. Besides VFX companies doing 360 degree video content or Responsive VR, VR could also become a solid component supporting the normal VFX workflow. Chris Edwards from The Third Floor states, “We’re confident that this market will continue to grow and we are actively preparing to meet the demand for content creators. There are many roads we can go down in entertainment and, unlimited potential“(Robinson, 2017).

But there is still the question if VR could reach the final stage of Gartner’s Hype Cycle and end in a mainstream adoption or if VR could “falter and become the industry’s next “3D”” (Weber, 2016).One important thing right now is definitely finding the need or reason for the technology and defining in which areas it makes most sense to use VR and to create alluring content for the costumers. One thing all VR creators have in common is “Finding creative reasons for using the new technology is what drives us, and we're all trying to see how we can push things further – that's the most exciting thing!” (Robinson, 2016).

What happens in the next few years is almost impossible to forecast. The future of VR is still quite undefined and there are several issues to solve. HTC’s vice president Dan O’Brian mentions concerning the future of VR “I hope that there’s still human interaction, and we don’t go full Matrix” (Mokey, 2016). He “hopes his son will grow up in a world where people still primarily interact face to face, even if they have the benefit of occasionally doing so virtually” (ibid.).

8

CONCLUSION

"2016 WAS NOT 'THE YEAR OF VR.'
IT WAS THE YEAR OF THE START OF VR."

– (Hamilton, 2016)

Figure 118: Illustration of Darrow; Everett Collection (Andrews); F. Martin Ramin/The Wall Street Jounal (Headsets).

“It was the year of the start of VR” (Hamilton, 2016). Last year VR was revived. It is a current subject which is represented on all major technical fairs and exhibitions and gains more and more public attention. VR is in constant change and new projects and progress will push development further. But the question is how long VR will stay this time and whether Sutherland's idea of ‘The Ultimate Display’ could ever become reality.

The goal of this thesis was to introduce VR as medium, show at which points VFX and VR converge and how the both industries affect each other. As VR is only in its beginnings, it starts to develop in different kind of areas and one of them is the VFX sector.

Due to the topicality of the subject, it was difficult to use classical scientific sources for the scope of this thesis. There are some books available concerning VR but as VR is increasingly developing into an industry of digital age, developments and information are mainly found in the internet. Furthermore, due to VR is a relatively young and rapid industry, there are many areas that are not fully researched. The terminology is not properly defined yet, so the result is that often only opinions and miscellaneous approaches of different people are merely described and not fully validated. Besides internet research, various conversations with people working with VR and/or VFX have been conducted in order to gain an insight into the VR sector from those who are directly affected by the new medium. The results of the asked questions and the discussed topics of the conversations were incorporated and integrated into the thesis.

For the purpose of achieving the objectives, conceptual and substantive foundations for VR as a medium were illustrated in order to create a core understanding of Virtual Reality. The main problem of not consistent terminology and its resulting controversy about the definition of ‘What is VR?’ was presented and explained. After that, three main interfaces between VR and VFX were defined for the aim of this thesis. The first contact point between these two was the use of VR as a tool to enhance the VFX workflow. Different ways to apply VR as a tool were presented such as for example for Virtual Production, for improving actors’ performances, as artist- and creation or communication tool. Often, however, these tools have only been used as a prototype and have not been adequately tested so that it is not certain whether these tools will prevail in the future and whether they will have sufficient benefit for integration into the VFX workflow. Moreover, it depends how the whole pipeline will develop in the future and at which parts VR as a tool could integrate. The next connection was made through VFX techniques that can also be applied to ‘Responsive VR’. 3D software for environment or asset production as well as common capturing techniques such as LiDAR or photogrammetry can be used as well for building interactive VR experiences. There are some successful attempts from VFX-sensitive companies in Responsive VR such as for instance the interactive ‘Martian VR Experience’ form The Third Floor. But one needs to be aware that for creating interactive experience a game-engine is needed and therefore other working methods are required than in the common VFX workflow. 360 degree video is the form of VR which is easier to integrate in the common VFX workflow and is the third highlighted connection between VFX and VR. Like described in the chapter 4 the 360 degree workflow has a lot of hurdles even if it is quite similar to the common VFX workflow. It is often the case that common VFX tools are shoehorned to comply with the needs of VR. A lot of tasks are improvised as there are no specialized tools for VR formats available. So it is most notably a high level of ingenuity which makes VFX studios and artists suitable for the emerging area of VR. “Long has there been a tradition in special and visual effects for artists to get their hands dirty, innovate and find solutions to on-set and post production problems. That same ingenuity is required in the still somewhat nascent VR industry” (Failes, 2016).

In the future, improvements in real-time technology and volumetric capturing as well as lightfield could completely change the way of working. There will be new tools and it could happen that through the converging of games and VFX there will evolve a new workflow that is applicable for all mediums. But at the moment the VR sector lacks people who are well-versed in the subject and as the medium is quite new there are hardly any seniors and experts in the field of VR. Most people working in VR right now transitioned from another profession for instance VFX or games. They experimented and trained themselves over the last years. So the VR sector really needs skilled craftsmen that understand the medium. Additionally, it is also difficult to find people that are working in VR because there is no real base for the VR sector and there are no real job descriptions established yet. Consequently there is also a problem of terminology for several tasks within the VR workflow. Such as VFX has rotoscoping or CG artists, VR needs job descriptions for e.g. ‘stitching artists’. Another issue is that there is barely education available such as for example courses in universities or even a degree program which only consists of VR technology and development. But everything is changing and every project brings new insights and experiences. The case study presented in chapter 5 served as an application example for a 360 degree workflow with VFX and should underline the information that was given in chapter four which concerned such a usual 360 degree VFX workflow.

A question which is decisive for the future of VR is ‘In which areas VR will make sense in future?’ And from that, it should be to ask whether it makes sense that VFX companies create VR experiences. Until these questions are not solved and VR has not established a suitable business model, VFX will still be the main source of revenue of VFX companies, with VR as additional experimental and developing medium besides that. The future of VR and which role VFX companies will play will only be known in the next few years. If VR gains more public awareness, computing power increases and the demand for VR content grows, perhaps there will be more VFX companies considering dealing with VR or it may be like Michele Sciolette said “a common task for visual effects houses in the relatively near future” (Edwards, 2015). The future of VR is almost impossible to map (cf. O'Brien, 2016). Gary Vaynerchuk, Founder and CEO of VaynerMedia, talks in the foreword of the book "The Fourth Transformation: How Augmented Reality and Artificial Intelligence Change Everything" about people predicting to never do something. Such as for example people say they will never blog or use Facebook or Snapchat and then after a while they will start to use these applications and slowly they will get integrated in their all day lives. He mentions that VR could be the next of such 'nevers' (cf. Scoble, & Israel, 2017, p.xv). To put it into the words of Mark Zuckerberg:

"VIRTUAL REALITY WAS ONCE THE DREAM OF SCIENCE FICTION. BUT THE INTERNET WAS ALSO ONCE A DREAM, AND SO WERE COMPUTERS AND SMARTPHONES. THE FUTURE IS COMING"

(Zuckerberg, 2014).

Figure 119: Mark Zuckerberg arriving at the MWC 2016 during the Samsung Press Conference.

9

APPENDIX

Figure 120: People with Samsung Gear at Mobile World Congress 2016.

9. 1 LIST OF ABBREVIATIONS

2D	two dimensional
3D	three dimensional
4K	resolution/4,000 pixels
AR	Augmented Reality
ASCII	American Standard Code for Information Interchange
ATAP	Advanced Technology and Projects
CAVE	Cave Automatic Virtual Environment
CC	Colour Correction
CCO	Chief Costumer Officer
CE	Consumer Edition
CEO	Chief Executive Officer
CES	Consumer Electronics Show
CG	Computer Graphics
CGI	Computer Generated Images
CTO	Chief Technology Officer
DCC tools	Digital Content Creation tools
DK	Developer Kit
DOF	Degree of Freedom
DOP	Director of Photography
DSLR	Digital Single-Lens Reflex
EU	European Union
EVL	Electronic Visualization Laboratory
FMX	International Conference on Animation, Effects, VR, Games and Transmedia
FOR	Field of Regard
FOV	Field of View
GDC	Game Developers Conference
GIF	Graphics Interchange Format

GUI	Graphical User Interface
GVRA	Global Virtual Reality Association
HDR	High Dynamic Range
HIT Lab	Humant Interface Technology Lab
HMD	Head-Mounted Display
HRFT	Head-Related Transfer Function
HTC	High Tech Computer Corporation
IBM	International Business Machines Corporation
IFA	Internationale Funkausstellung (Messe für Consumer Electronics und Home Appliances)
ILD	Interaural Level Differences
IMU	Inertial Measurement Unit
IPD	Interpupillary Distance
IR	Infrared
ITD	Interaural Time Differences
Latlong	Latitude/Longitude
LCD	Liquid Crystal Display
LED	Light Emitting Diodes
LiDAR	Light Detection and Range
LOD	Level of Detail
MoCap	Motion Capturing
MoCo	Motion Control
MR	Mixed Reality
MS-DOS	Microsoft Disk Operating System
MWC	Mobile World Congress
NCEM	National Centre for Early Music
obj	file format developed by Wavefront Technologies
ODS	Omnidirectional Stereo
OLED	Organic Light Emitting Diode

PC	Personal Computer
POV	Point of View
Previs	Previsualization
PS4	Play Station 4
PSVR	Play Station Virtual Reality
px	Pixel
RGB	Red-Green-Blue
RnD	Research and Development
SAN	Storage Area Network
SDI	Serial Digital Interface
SDK	Software Development Kit
SIGGRAPH	Special Interest Group on Graphics and Interactive Techniques
TV	Television
UI	User Interface
USC	University of Southern California
UX	Users Experience
VE	Virtual Environment
VES	Visual Effects Society
VFX	Visual Effects
VPET	Virtual Production Editing Tool
VPL	Visual Programming Lab
VR	Virtual Reality
WWW	World Wide Web

9.2 GLOSSARY

3ds MAX:	Modeling, animation and rendering software.
4K, 6K, 8K, 10K:	Different resolutions. (e.g. 4K = approximately 4000 pixels of horizontal resolution).
Accelerometer:	A sensor to measure acceleration.
Adobe After Effects:	An industry-standard tool for video compositing, motion graphics design, and animation by Adobe Systems.
Adobe Flash:	Is a platform for displaying and programming multimedial and interactive content.
Adobe Photoshop:	An image processing program by Adobe Systems for operating systems as MAC OS, Microsoft and Windows.
Adobe Premiere:	A commercial film and video editing program by Adobe Systems.
Ambisonic:	A technique to create full-sphere surround sound.
Android:	Operating systems for mobile phones.
Autodesk Maya:	A software for modeling, animation, simulation and rendering in 3D.
Binaural:	A method to record sound using two microphones that were arranged to create a 3D stereo sound feeling for the listener as if he were in a room with the interprets or the instruments.
Boo, C#, C++, Lua, Uniscript	Programming languages.
cineSync:	A software tool which was designed for viewing video content simultaneously with different people around the world.
C mount lenses:	Is a standard thread for lenses used on many movie cameras.
DaVinci Resolve:	A colorgrading tool.
Dolby Atmos:	Surround Sound technique by Dolby Laboratories.
Foundry Mari:	A 3D digital painting tool that allows detailed multi-layered textures to be applied directly to 3D models.
Green/Blue-screen:	A technique used in film and television which allows to place subsequent people or objects in front of a background that can be a real movie recording or computer graphics.
Houdini:	Program by Side Effects Software for e.g. procedural simulations.

Macintosh:	Operating system for Apple Systems.
Magnetometer:	Is a sensory device for measuring magnetism
Modo:	An integrated software package for 3D modeling, texturing and rendering from Foundry.
Motion Control (MoCo):	Technique that uses robotic camera equipment to provide programmable and repeatable amera movement during shots.
MS-DOS:	First operating system of Microsoft before invention of Windows.
MudBox:	A 3D graphic software that allows you digital sculpting and digital painting.
Nuke:	A software for visual effects and compositing used for the professional sector in film and video postproduction, developed and distributed by Foundry.
Object Oriented Programming (OOP)	Programming language model which is based on 'object' rather than actions. One of the most influential developments in computer programming.
Quicktime:	A multimedia software architecture for operating systems as MacOS and Windows.
Shotgun:	A software that makes project management tools helping creative studios to review, schedule, track and manage their digital assets.
Slack:	A web-based instant messaging service for communication within working groups developed by Slack Technologies.
Software Development Kit (SDK)	Set of software development tools which enable creation of applications. SDKs are available for software packages or framework, hardware platform, computer systems, etc.
SynthEyes:	A program for tracking and matchmoving.
Vray, Arnold, Mantra:	Renderer.
Windows:	Operating System from Microsoft.
Zbrush:	Is a digital painting and sculping program.

9.3 MENTIONED COMPANIES

3DEXCITE	www.3dexcite.com
3Lateral	www.3lateral.com
8i	www.8i.com
AltspaceVR Inc	www.altvr.com
Animal Logic	www.animallogic.com
AOC Archaelogy Group	www.aocarchaeology.com
AOC Archaelogy Group	www.aocarchaeology.com
Apple	www.apple.com
ARRI	www.arri.com
Autodesk	www.autodesk.de
AutoPanoVideo	www.kolor.com
Axis Animation	www.axisanimation.com
Blackmagic	www.blackmagicdesign.com
Bullitt - Production Company	www.bullittbranded.com
CCP Games	www.ccpgames.com
Cinesite	www.cinesite.com
CineSync	ww.cospective.com
Crytek	www.crytek.com
Cubic Motion	www.cubicmotion.com
Cyberith Virtualizer	www.cyberith.com
Digital Domain	www.digitaldomain.com
Disney	www.disney.com
Double Negative	www.dneg.com
DreamWorks Animation	www.dreamworksanimation.com
Emblematic Group	www.emblematicgroup.com
Epic Games	www.epicgames.com
Europapark	www.europapark.de

Evil Eye Picture	www.evileyepictures.com
Facebook	www.facebook.com
Foundry	www.foundry.com
Framestore	www.framestore.com
fxguide	www.fxguide.com
Global Virtual Reality Association (GVRA)	www.gvra.com
Google	www.google.com
Google Jump	www.vr.google.com/jump
Google Spotlight Stories	www.atap.google.com/spotlight-stories
GoPro	www.gopro.com
High Fidelity	www.highfidelity.io
House of Moves	www.moves.com
HTC	www.htc.com
HypeVR	www.hypevr.com
IBM	www.ibm.com
Id Software	www.idsoftware.com
Ikea	www.ikea.com
Ikinema	www.ikinema.com
Ilion Anim Studios	www.ilion.com
Illumination MacGuff	www.illuminationmacguff.com
ILM	www.ilm.com
Iloura	www.iloura.com.au
Image Engine	www.image-engine.com
Jaunt Inc	www.jauntvr.com
Kolor	www.kolor.com
KonceptVR	www.konceptvr.com
LucidWeb	www.lucidweb.io

Luma Pictures	www.lumapictures.com
Lytro	www.lytro.com
Mackevision	www.mackevision.com
Magic Leap	www.magicleap.com
Mariott	www.marriott.com
Mechanism Digital	www.mechanismdigital.com
Method	www.method.gg
Microsoft	www.microsoft.com
Mikros Image	www.mikrosimage.com
Mirada	www.mirada.com
MK2	www.mk2.com
Motorola	www.motorola.com
MPC	www.mpc-hc.org
NBA	www.spox.com
NCEM	www.ncem.co.uk
New Deal Studios	www.newdealstudio.com
NextVR	www.nextvr.com
Ninja Theory	www.ninjatheory.com
Nintendo	www.nintendo.com
Nokia	www.nokia.com
Nordeus	www.nordeus.com
NVIDIA	www.nvidia.com
Oculus	www.oculus
Opaque Media	www.opaque.media
Ossic	www.ossic.com
Panocam	www.panocam3d.com
Perkins Coie LLP	www.perkinscoie.com
Philco Corporation	www.philco-intl.com
Pixar	www.pixar.com

Pixomondo	www.pixomondo.com
Playmatics	www.playmatics.com
Psyop	www.psyop.com
PtGui	www.ptgui.com
RealityVirtual	www.realityvirtual.co
RED	www.red.com
Rewind	www.rewind.co
Ricoh	www.ricoh.com
Rise FX	www.risefx.com
Samsung	www.samsung.com
Scanline VFX	www.scanlinevfx.com
Shotgun Software	www.shotgunsoftware.com
SilVRscreen Productions	www.silvrscreenproductions.com
Six Flags	www.sixflags.com
Slack	www.slack.com
Snapchat	www.snapchat.com
Sony	www.sony.com
Sony Interactive Entertainment	www.sie.com
Spark Capital	www.sparkcapital.com
StarVR	www.starvr.com
SuperData Research	www.superdataresearch.com
Take-Two Interactive Software	www.take2games.com
Technoprops	www.technoprops.com
Tendril	www.tendril.ca
The Mill	www.themill.com
The Molecule	www.themolecule.com
The Third Floor	www.thethirdfloorinc.com
The Venture Reality Fund	www.thevrfund.com
Trixter	www.trixter.de

UploadVR	www.uploadvr.com
Valve	www.valvesoftware.com
VaynerMedia	www.vaynermedia.com
Vimeo	www.vimeo.com
Virtuix	www.virtuix.com
Visbit	www.visbit.co
Volvo	www.volvocars.com
VRC The Virtual Reality Company	www.thevrcompany.com
VRTV	www.vrtv.io
Vuze	www.vuze.com
Weta Digital	www.wetafx.co.nz
Wevr	www.wevr.com
YouTube	www.youtube.com
ZTE	www.ztedevice.com

LIST OF FIGURES

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Figure 121: Illustration of Darrow, J. R. Eyerman/The Life Picture Collection/GETTY Images (audience), F. Martin Ramin/The Wall Street Journal (headsets).