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**DISSERTATION**

# VIRTUAL REALITY

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**DISERTAČNÍ PRÁCE**

# VIRTUÁLNÍ REALITA

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Vedoucí práce: Prof. MgA. Vladimír Smutný

Oponent práce:

Datum obhajoby: 24.6.2021

Přidělovaný akademický titul: Ph.D

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I declare that I have prepared my Dissertation independently on the following topic:

Virtual Reality

Under the expert guidance of my thesis advisor and with the use of the cited literature and sources.

Prague, 24.2.2021

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# Abstract

This thesis aims to grasp virtual reality as a complex, interconnected technology and multi-sensory medium. VR is currently experiencing a revival and rapid technological development accompanied by much experimenting with form and content. Following the historical, technical and philosophical roots that led the medium to its current state and by analysing several VR installations, the thesis explores the medium's possibilities and limits — mainly confronting the idea of VR being a narrative art form similar to film. In the second part, the thesis examines interactive CGI VR and sensory stimulation means, self-perception in VR and direct brain-computer interfaces.

The latest developments in VR point to three main conclusions. Firstly there is a departure from the failed storytelling attempts in VR to make it a social co-presence means — a more advanced way of meeting other people virtually. Secondly, there is a trend of VR-related technologies such as augmented or mixed reality blending with VR indicating that the use cases for these technologies will be much broader than entertainment. Finally, there is a clear convergence of VR and artificial intelligence, causing concerns over privacy, unbiased perception of reality, and generally unknown effects of long-term VR use. Despite being a predominantly visual medium having potential for creative forms of entertainment, virtual reality should not be understood as a storytelling medium. However, intersection with cinema is possible, when VR is used as a tool.

# Abstrakt

Cílem této práce je uchopit virtuální realitu jako komplexní, vzájemně propojenou technologii a vícesmyslové médium. V současné době zažívá VR oživení a rychlý technologický rozvoj doprovázený mnoha experimenty s obsahem i formou. Sledováním historických, technických a filozofických kořenů, které vedly toto médium k jeho současné podobě, a analýzou několika VR instalací, zkoumá práce možnosti a limity média — především konfrontuje myšlenku, že VR je formou narativního umění podobné filmu. Ve druhé části, práce zkoumá interaktivní CGI VR, prostředky pro stimulaci smyslů, vnímání sebe sama ve VR a rozhraní k přímému spojení mozku s počítačem.

Poslední vývoj ve VR ukazuje na tři hlavní závěry. Zaprvé dochází k odklonu od neúspěšných pokusů o vyprávění ve VR ve prospěch prostředku sociálního kontaktu, tzv. sociální přítomnosti — pokročilejší způsob virtuálního setkávání s jinými lidmi. Zadruhé se ukazuje trend splývání souvisejících technologií, jako jsou rozšířená, nebo smíšená realita s VR, což naznačuje, že užití těchto technologií bude mnohem širší než jen pro zábavu. A konečně, existuje jasná konvergence VR a umělé inteligence, což vyvolává obavy ohledně soukromí, nezaujatého vnímání reality a obecně neznámých účinků dlouhodobého používání VR. Přestože je virtuální realita převážně vizuální médium s potenciálem pro tvůrčí formy zábavy, neměla by být chápána jako médium k vyprávění příběhů. Průnik s filmem je možný, ale jen v případě, je-li VR nástrojem.

# Acknowledgements

Completing this dissertation would not have been possible without the input and help of many people with whom my paths have crossed at FAMU and elsewhere. I want to thank professor Marek Jícha who persuaded me to continue my studies at the Department of Cinematography as a postgraduate student. My sincere thanks go to my advisor, professor Vladimír Smutný. Firstly for steering me away from my initial idea of writing about the aesthetics of stereoscopy, and pointing my attention towards virtual reality. Secondly, for his valuable input and the open-minded attitude with which he approaches any discussion. They were always thought-provoking.

I would also like to thank Ondřej Bach and Jakub Kučera of DIVR Labs, who trusted me to collaborate with them on the Meet The Dinosaurs VR experience. The seven days I had spent with them, and everyone else at DIVR Labs was perhaps the most insightful and enjoyable time spent on this dissertation.

Finally, I would like to thank all my colleagues and students at the Cinematography Department of FAMU. It’s you who makes it special there.

# Preface

The only way of discovering the limits of the possible is to venture a little way past them into the impossible.[1]

— Arthur C. Clarke

This thesis was initially intended to deal with the aesthetics of stereoscopy — a logical continuation of my 2013 Master's thesis titled Stereoscopy and the Cinematographer[2]. I was stubborn enough to write about stereoscopy, which has a history of emerging for a short period and then disappearing again about every 30 years. Believing that this time, it would be different, that stereoscopic films would stay — at least as a sideline to conventional films. Besides, there were some considerable arguments in favour. The main one being that the wave of stereoscopic cinema, which skyrocketed in 2009 with James Cameron's Avatar, was the first digital wave. Never had stereoscopic films been shot with digital cameras with previously unthinkable aid of computers and robotic rigs. Screening too was digital, and the picture quality for the needs of good stereoscopy was unprecedented.

After a few years, it still looked promising. The most problematic technical issues had been fixed, and most directors and cinematographers seemed to have a proper understanding of the "new" way of creating depth on screen and making that technique a part of the storytelling. One such director was James Cameron, who truly understood the intricacies of stereoscopy. As an avid proponent of stereoscopy, Cameron made once a comment that became widely cited: "For me

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[1] Clarke's second law.

[2] Written in Czech as Stereoskopie a kameraman.

it's absolutely inevitable, that all entertainment will be 3D… it will all be 3D eventually, because that's how we see the world." [1] Many acclaimed directors — Martin Scorsese, Werner Herzog, Wim Wenders and Ridley Scott to name the most prominent — directed films in 3D, as stereoscopy was (and still is) popularly called.

Immersion was the word of choice used to sell the illusion of the third dimension. Furthermore, there was a noticeable aesthetic emerging in stereoscopic filmmaking. Just like James Cameron, other filmmakers embraced the third dimension and enriched film language with it too. Not all may agree with this statement, but films like Pina[3], Life of Pi[4] worked with the possibilities of stereoscopy as an organic part of the film. For many other S3D (stereoscopic 3D) films, the illusion of depth was just a gimmick to draw audiences promising an immersive experience eventually to justify the higher ticket price.

Nevertheless, as expected by many, stereoscopy again slowly faded out around the mid-2010s. A few S3D films are still being shot, but nothing out of the ordinary like Pina. Besides, films screened nowadays as stereoscopic 3D films are rarely shot in stereo, but are post-converted to S3D. A process which is cheaper and more simple than shooting stereoscopic, but not as visually precise and rich as native S3D.

About at the same time, virtual reality started making headlines. Though a reemerging technology in a certain sense too, it is accompanied by a wave of optimism not quite unlike the optimism of S3D films staying around in the 2010s. It was then, when my advisor, prof. Vladimír Smutný discussed changing the topic of the dissertation to Virtual reality, which he claimed to be much more prospective than stereoscopy in repeated retreat. It was hard to imagine such a

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[3] Dir. Wim Wenders, DOP Hélène Louvart AFC and Jörg Widmer, 2011.

[4] Dir. Ang Lee, DOP Claudio Miranda ASC, 2012.

change, after feeling comfortable in a topic I already had spent a few years with. It took a while to start understanding Virtual reality and how (and if) it fits into the world of cinematography.

This thesis is an attempt to understand virtual reality in its complexity and as a whole. From a cinematographer's perspective, naturally, but not limiting the examination to film-centric thinking. Not in the sense of mapping VR's ever-evolving technical state and not in the sense of making a guide how to do this or that in VR, but by confronting and analysing historical and contemporary concepts of VR, exploring its roots, possibilities, applications, potential and impacts to various areas of human life and endeavour.

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Any sufficiently advanced technology is indistinguishable from magic.[5]

— Arthur C. Clarke

[5] Clarke's third law.

# 1. Introduction

## 1.1. Paracosma, the First Virtual World

"But what is reality?" asked the gnomelike man. He gestured at the tall banks of buildings that loomed around Central Park, with their countless windows glowing like the cave fires of a city of Cro-Magnon people. "All is dream, all is illusion; I am your vision as you are mine." [2]

These are the opening lines of Stanley Grauman Weinbaum's short story Pygmalion's Spectacles. Originally published in Wonder Stories, an American science-fiction magazine in 1935. The story is believed to be the first envisioning of what we today call virtual reality. [3]

The story revolves around Dan Burke, a young man strolling in New York's Central Park, trying to get back to his senses after having drunk too much alcohol. Dan meets an elderly and a rather grotesque figure, professor Ludwig, who confronts him with the question of what is dream and reality. The discussion continues in the professor's hotel room, where he demonstrates a device for dreaming called spectacles — a contraption with goggles and a rubber mouthpiece, something that looked distantly as a gas mask. Dan, with the goggles on, is transported to a world (Paracosma) where he meets two other figures. The young beautiful Galatea and Leucon, an older man. Dan, immediately drawn into the beautiful world of Paracosma, sets off for an adventure of discovery with Galatea. The demonstration ends, and Dan Burke returns to reality, longing for the beautiful Galatea.

## 1.2. Dreaming of Paracosma

Though the story at the end reveals how all the magic seen by Dan was achieved — and it is quite far from how virtual reality (VR) as we know it really works — it is remarkable, how close Weinbaum got in his description of the dreaming apparatus to many aspects of contemporary VR. In a comment made by professor Ludwig, Weinbaum predicted the connection and perhaps even love-hate relationship between the film industry and VR — "… I bring it here to sell to Westman, the camera people, and what do they say? 'It isn't clear. Only one person can use it at a time. It's too expensive.' Fools! Fools!" — clearly hinting the Eastman Kodak Company. The item offered for sale is, of course, what we would call a VR headset. Weinbaum's spectacles are not only audiovisual but olfactory and haptic too. The story predicted multi-sensory VR. There are flashes of it, but a perfect working example remains elusive to technology, like Galatea to Dan Burkes.

Weinbaum also correctly predicted that images in such a dream machine would be stereoscopic. As a science fiction writer, he must have been familiar with stereoscopy. Pygmalion's Spectacles were published in 1935. Stereoscopic cinema boomed shortly between 1952—1955, but ever since the invention of stereoscopic images in 1838, there had been some experimenting done in stereoscopic cinema. It was more of an exploration of the technical possibilities than anything else. Nevertheless, 1922 gave birth to the first stereoscopic feature film — The Power of Love[6]. Weinbaum could have been aware of this and used the technology in the story as a novelty. If not for his untimely death in 1935, at the age of 33, he would have lived to see the mass popularisation of stereoscopic images through the View Master in 1939.

Weinbaum's intuition was also correct when he touched on the subject of self-awareness in VR. Dan Burke sees himself through the spectacles as barefoot, though he is wearing shoes in reality. A glimpse of what we call an avatar today. Perception of oneself in a virtual world will be discussed later.

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[6] Dir. Nat G. Deverich, DOP Harry K. Fairall, silent, USA, 1922.

Another rather accurate prediction in Pygmalion’s Spectacles is the intricacy of storytelling in VR. Though vaguely, Weinbaum implied that the person experiencing a virtual world would be limited in possible actions and interactions with the world. Where to go, what to say, what to do, expecting a certain kind of feedback resembling the real world, etc. Paracosma is strongly governed by predetermined “laws” that its inhabitants are aware of. What can be said and done and when that is possible. However, they do not know the origins of the laws, neither their purpose nor creator. When Dan questions Galatea or Leucon on these laws, the answers imply a predetermined storyline, that they don’t challenge: “Ours… are the unalterable laws of the world, the laws of Nature. Violation is always unhappiness.” [2] Dan’s attempt to break the laws at the end of the story results in his forceful banishing from Paracosma back to the real world. For him, though, it is like fighting a dream that is supposed to come to an end. This again is closely similar to today’s state of VR, where no VR experience yet offers total freedom of action and perfect interaction with the virtual world.

Dan Burke’s perception of (the real) time, while in Paracosma, was distorted — precisely as it would be for anybody in a VR simulation. Although when Dan and Galatea meet, Galatea tells Dan that his stay will be “until the second noon from this,” however his time with the spectacles oh his face in the hotel room was about 5 hours.

Combined, all these experiences are what makeup immersion — an acceptable level of suspension of disbelief induced by visual, auditory, haptic and olfactory stimuli generated by the VR system itself and perceived by the user as originating in the virtual world. At present, VR can be fairly convincing with visuals and audio. The rest is still very experimental, limited in use, or not very likely to be adopted by a broader user base.

Perhaps what is most remarkable in Weinbaum's story is the parallel of virtual reality and dreaming. Dreaming as the essence of VR is one definition of VR written by Jaron Lanier, the "father" of modern VR. His third definition of VR states: "Hope for a medium that could convey dreaming." [4]

## 1.3. What Is Virtual Reality?

There are multiple answers to such a question. The Encyclopaedia Britannica defines virtual reality as follows: "Virtual reality (VR), the use of computer modelling and simulation that enables a person to interact with an artificial three-dimensional (3-D) visual or other sensory environment. VR applications immerse the user in a computer-generated environment that simulates reality through the use of interactive devices, which send and receive information and are worn as goggles, headsets, gloves, or body suits…" [5] Though the definition is clear, some might argue that VR is not a simulation of reality but a simulation of a world or environment. The difference is not purely linguistic. A VR simulation does not necessarily follow the laws of nature — one can fly in such a simulation, or look at objects in unreal scales, which is not a simulation of reality.

One of the pioneers of the filed (perhaps the most important one) and the person who coined the term "virtual reality[7]", Jaron Lanier, gives a much more poetic insight: "First VR Definition[8]: A twenty-first-century art form that will weave together the three great twentieth-century arts: cinema, jazz, and programming." [4]

Both aforementioned definitions are accurate about some aspects of VR, though the latter may come across as a little far fetched and thus vague if one is not too

[7] The terms virtual reality and virtual matrix appeared in The Judas Mandala, a 1982 science-fiction novel by Damien Broderick. However, it was after Lanier started using the term.

[8] Jaron Lanier offers over 50 definitions of VR.

acquainted with the subject. Regardless of definition, there is no simple and straightforward answer to the initial question that would simultaneously be precise and holistic. Virtual reality is not intrinsic.

It is one of those questions with many aspects like "What is time?" or "What is consciousness?". Physics still does not have a definitive answer to what time is, although it can measure it and knows some of its properties. For instance, that time is relative as Einstein discovered. However, we do not know time's true nature or if (or how) it is related to the fundamental four forces. Neither is the ability to measure time perfect. Cosmologists are not able to say what happened before about $10^{-43}$ seconds after the Big Bang. In this infinitesimally short episode (for the lack of a better expression that would not imply time), the very concept of time becomes meaningless.

Medicine, or any other exact science, also does not answer what consciousness exactly is, let alone where in the brain it may reside. A new theory suggests that it is found in the electromagnetic field generated by the brain. [6] Nevertheless, psychologists and psychiatrists know how to work with it and alter it. Luckily, so do anesthesiologists. Philosophy (western and eastern), ever since its existence is drawn to explaining the phenomenon too. Depending on one's own worldview and inclinations, those explanations can be more or less satisfying. Though, still without the answer what consciousness *is*.

In this light, doubt arises whether the question (What is VR?) is valid at all. Do we really need a sharply delimited definition of what virtual reality *is*?

Galilean relativity made clear that motion can exist only in a frame of reference. Einstein proved that even time is relative, dependant on a frame of reference too. Nothing can exist inherently. If anything existed inherently, it could not have arisen from a cause or conditions. Inherent existence would deny causality.

Nothing could rise, change, nor cease to exist. Each object and phenomenon is interdependent with other objects and phenomenons. Therefore we cannot isolate virtual reality to study it.

The VR technosphere is developing so rapidly that whatever is written about VR now can become very soon obsolete. Therefore the investigation of VR should examine it from various perspectives and explore its roots and interdependencies with other fields such as art, economy, technology, and perhaps even ethics. The current perception of VR is fragmented and somewhat compartmentalised — concentrating only on particular aspects of the medium, overlooking its complex and technologically convergent nature. Moreover, VR is often viewed uncritically, based on misconceptions.

We must shed the idea of a virtual reality that *is*. If we want to understand it, we must approach it with precisely the kind of broad-mindedness woven into Jaron Lanier's first definition of VR. Simultaneously keeping in mind the ever-evolving nature and potential of virtual reality artfully expressed in Lanier’s 3rd definition of VR: “Hope for a medium that could convey dreaming.” [4]

# 2. Stereoscopes and Depth Perception

## 2.1. Stereopsis

Virtual reality headsets display 3D images utilising stereopsis — the perception of depth made possible by a small lateral disparity of our eyes, which causes each eye to see a slightly different (laterally shifted) two-dimensional projection of reality on the retina. The visual cortex processes (fuses) the two images and in turn, we perceive a three-dimensional image of the world. Stereopsis makes it possible to see depth, volume and judge relative distances and placements of objects in our visual field. That is if we have a healthy binocular vision.

This physiological process can be taken advantage of by presenting the observer a set of two-dimensional images (one for each eye) that have a slight lateral shift in perspective. The two images are fused, and the brain is tricked into believing it sees an actual 3D scene and not two flat monocular images.

## 2.2. Wheatstone Stereoscope

The first person to demonstrate stereopsis was a professor of experimental philosophy Sir Charles Wheatstone (1802—1875). In 1830 he created a device called the reflecting mirror stereoscope[9]. A rather bulky apparatus that used two mirrors sharing a common edge and angled at 90° which reflect two separate images into the eyes of the observer. Wheatstone discusses his finding in detail in his paper [7]. The pictures in Wheatstone's stereoscope had to be line drawings because it was not until 1839 the world knew of photographic processes like daguerreotypes and later Talbotypes and Calotypes. A fact that Wheatstone acknowledges with great respect in his later paper [8]. He first presented his discovery at the Royal Society of Great Britain in 1838. This is why the invention of the Wheatstone stereoscope is sometimes dated to 1838 and not

[9] From the Greek words skopion and stereo — to see solid.

1830. Soon after the invention of photography, Charles Wheatstone asked Henry Fox Talbot to create photographic stereo pairs of "full-sized statues, buildings, and even portraits of living persons." [7]

Wheatstone points out that the proper positioning of the cameras for shooting stereoscopic photographs with a "correct binocular perspective" requires the optical axes of their lenses to be at an angle of 18°, which happens to be the angle of convergence of the observer's eyes looking at the pair of stereo photographs in his stereoscope. He claims that regardless of the distance of the photographed object, the cameras must be placed on the circumference of a circle where the photographed object is at the centre of the circle while the cameras are 18° apart in angular distance. Though Wheatstone did not put much importance to these instructions, as he called them, he silently lay foundations to the two most important parameters of stereography — interaxial distance and convergence, which will be discussed later.

## 2.3. Brewster Stereoscope

Scottish born Sir David Brewster (1781–1868) was a scientific rival of Charles Wheatstone. Brewster published numerous papers and books on optics and related fields but is perhaps best known for a toy he invented in 1816 — the kaleidoscope. Followed in 1856 by a modernised stereoscope later known as the Brewster lenticular stereoscope. In the same year, Brewster published a book [9] on his stereoscope.

Brewster strongly opposed Wheatstone being the first to discover the principle of binocular vision. Putting great effort into researching and citing writings of Euclid, Leonardo da Vinci and Jesuit mathematician François d'Aguilon to name a few, Brewster vehemently tried to prove that Wheatstone, inspired by earlier findings, appropriated the idea of binocular vision.

Brewster also took every opportunity to mock and scorn Wheatstone and his stereoscope e. g., "In Mr. Wheatstone's stereoscope he employs two mirrors, each four inches square that is, he employs thirty-two square inches of reflecting surface, and is therefore under the necessity of employing glass mirrors, and making a clumsy, unmanageable, and unscientific instrument, with all the imperfections which we have pointed out in a preceding chapter." [9] In numerous other mentions, he kept contesting design choices, usability as well as cost-efficiency.

Regardless of Brewster's envy of his fellow scientist, his innovation of the stereoscope was significant. He came with a compact design that could be easily hand-held. Instead of mirrors, he used a set of two lenses (like the eyepieces of a binocular) attached to a pyramid-like shaped wooden box. The stereo pair to be viewed was slid in from the side. Depending on if the pair were photographed on paper or transparent templates, a small lid could be open to let light in and illuminate the photographs, or the lid could be closed, and the stereoscope would have to be pointed to a light source, just like when viewing slide film. In fact, Brewster's stereoscope quite resembles a VR headset. Both devices are lenticular, after all.

Unlike Wheatstone, Brewster went into a great deal of detail on the photography of stereo pairs[10]. Neither in this matter did he forget to jab Wheatstone of being amateurish: "Such is Mr. Wheatstone's rule, for which he has assigned no reason whatever." [9]

Firstly, Brewster proposed using binocular cameras, especially for portraits: "In order to take binocular portraits for the stereoscope a binocular camera is

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[10] Brewster dedicated a whole chapter of 28 pages to the subject, while Wheatstone dealt with it in about half a page. Though Wheatstone wins when it comes to the clarity of writing and practicality of the instructions (author's note).

required, having its lenses of such a focal length as to produce two equal pictures of the same object and of the proper size." [9]

His further findings on creating "perfect representations" could be briefly summed as follows:

- The aperture of the lens should be equal to the aperture of the human eye
- Interaxial distance should equal to the average distance between human eyes
- The distance of the photographs in the stereoscope to the eyes must be equal to the focal distance of the camera lens

Although it displayed only static photographs, the stereoscope (Wheatstone's and Brewster's) was the first device to come close to convey visual immersion. About 40 years before the birth of cinema, seeing something as engaging as 3D photographs, was the closest many people could ever get to catching sight of exotic lands and visiting places out of reach. It is therefore not surprising that stereoscopes made a notable dent in the pop-culture of their time. Queen Victoria got one as a present in 1851 and found it "greatly pleasing" [10]. Three years later the London Stereoscope Company was founded, and shortly after it was renamed to the London Stereoscopic Company. Selling stereoscopes and stereoscopic photographs, the company flourished. It is still in business and runs an E-shop[11]. The managing director is Brian May, the astrophysicist and guitarist of Queen[12].

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[11] https://www.londonstereo.com

[12] https://youtu.be/dDYfEM03abA

## 2.4. Interaxial Distance and Convergence

Interaxial distance (sometimes also called the stereo base) is the distance between the optical axes of the lenses[13]. The wider the distance, the stronger the stereoscopic effect. Objects will appear to be more voluminous with a larger interaxial and flatter when the camera pair is closer together.

Convergence is the angle at which the optical axes of the lenses cross. Shooting with a non-zero angle of the optical axes is what is today known as shooting converged in stereography. Keeping the optical axes parallel is called shooting parallel.

When viewing two images shot parallel, everything will appear to be in front of the image plane — the imaginary plane where the images are physically projected or printed on. Only objects in infinity where the parallax[14] is zero will be seen on the image plane. By convention, the space in front of the image plane is called negative space, and space behind it is called positive space. It is because of the negative, respectively, positive parallaxes. Therefore sometimes the synonymous terms positive and negative parallax is used.

Converging the lenses controls the depth placement of objects in the image. At the convergence point, objects have no lateral disparity, and therefore they will be seen on the image plane. Everything between the convergence point and the camera will appear as being in front of the image plane. Objects behind the convergence point will occupy space behind the image plane. This logically leads to the question, how objects in infinity would appear because of their large lateral disparity.

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[13] Interaxial distance is at times confused with interocular distance, which refers to the lateral distance of our eyes.

[14] Parallax is the relative position of an object in a pair of stereoscopic images.

### 2.4.1. Divergence

There is a limit to the depth of a stereoscopic image that can comfortably be viewed. The word comfortably is important. When the photographed object is too close to the camera, the fusion of the images becomes uncomfortable, or even painful. This is because their lateral disparity is too wide and our eyes have to converge too strongly to see a 3D image. It is the same as trying to focus on something physically too close to us — it becomes painful. When the photographed object is too far away from the convergence point, the parallax becomes too large and fusing the two images would require our eyes to diverge. Left-eye image is too far left, Right-eye image is too far right. Under normal circumstances that never happens, it is completely unnatural. Even when looking at a very distant object like a star, our eyes have a very slight non-zero convergence angle. However, when viewing a stereoscopic image, where the parallax exceeds the human interocular distance, eyes are forced to diverge to fuse the pair of images. The average interocular distance for an adult it is about 64 mm, less for children. Depending on how strong the divergence is and how long the viewer is exposed to it, it can cause anything from an uncomfortable feeling to a painful experience including nausea, headaches and vomiting.

Parallax is proportional to the interaxial distance and image size (screen size for stereoscopic cinema) and is affected by convergence. The greater the images (screen), the larger the risk of running out of the so-called stereoscopic real estate and running into the feared divergence at stereoscopic infinity. This is always a concern for stereoscopic films, mainly when intended for huge screens like IMAX. Given the small sizes of Wheatstone's drawings and eventually photographs (at most roughly double the size of a postcard), it is highly unlikely he had to deal with divergence as long as the images were viewed as intended — with the main object on the image plane.

### 2.4.2. Convergence and Accommodation

Divergence is not the only physiological challenge one might face in viewing stereoscopic images. When looking at an object, eyes perform two fundamental actions — convergence and accommodation.

The convergence of the eyes is their inward rotational movement making their optical axes to intersect on the observed object. Accommodation is the action of the eye muscles stretching or contracting to change the shape of the eye lens so it can focus on the observed object. Under normal circumstances, these actions are coupled. However, not when looking at a stereoscopic pair. The convergence of the eyes keeps changing depending on which part of the image they are looking at — how large horizontal disparities are being fused. Nevertheless, accommodation remains unchanged as both images are physically at a constant distance from the eyes. No change in focus is necessary.

Though decoupled convergence and accommodation is unphysiological, it is a skill that can be learned even without understanding the underlying mechanism. It is a matter of a few seconds or minutes until one becomes good at it. In the early 1990s stereograms became popular — images with strange repetitive patterns that made no sense at first sight. Nevertheless, when stared upon in a certain way, a faint camouflaged 3D object would emerge from the jumbled patterns. That stare is a volitional desynchronisation of convergence and accommodation. Fortunately, viewing a stereoscopic image or film is much easier, and the same applies to seeing virtual reality through a VR headset.

## 2.5. Orthostereoscopy

A 3D image is orthostereoscopic when it perfectly replicates human vision. With this technique, it would be impossible to see a difference between the original scene and its representation. The geometry and perspective are natural, and the perceived sizes are equal to the original ones. [11]

The illusion of an orthostereoscopic projection is almost perfect, and eye fatigue is minimal compared to non-orthoscopic projections because of the physiological similarity to seeing in the real world.

A 3D image is orthostereoscopic when:

- Captured with an interaxial equal to the human interocular distance
- The camera lenses have the same field of view as the human eye
- The viewing angle of the image is equal to the field of view of the lens

Since the viewer does not see the frame in a VR headset, or ideally is not supposed to, the third condition for orthostereoscopy would have to be slightly modified: The perceived angular size of a virtual object is equal to the angular size of the same physical object. The distance between the screens would have to be adjusted to match the viewer's interocular distance. This parameter affects the viewing comfort but has no impact on the orthostereoscopy itself.

Orthostereoscopy is a special case of stereoscopy, and the conditions for it cannot always be met. It is practically impossible to achieve orthostereoscopic projection in the cinema because every member of the audience is seated somewhere else. Also, not every shot is shot with a lens of a normal focal length. Orthostereoscopy is only possible when there is perfect control of all these elements, like in theme park rides, where the stereoscopic projection would serve as an extension of the physical set. However, the most desired and sensible application of orthostereoscopy is in virtual reality, where the creators have extremely high control over creating and presenting the 3D image. The observer’s position to the screens in the headset is constant and so can be taken into the entire design of the stereography.

### 2.5.1. Orthostereoscopy vs. Good Stereoscopy

It is still a common misconception, that good stereoscopy means having the interaxial equal to the interocular distance. This argument is not entirely valid because the proponents are not considering other aspects of the issue.

Firstly, even the earliest findings of Charles Wheatstone imply that a change of the interaxial does not impair a correct binocular perspective. Sadly though as Wheatstone only subcontracted Talbot to provide the photographs, he was not too elaborate on the photographic process itself. There are no notes about the used equipment, and therefore one can only assume that very rudimentary lenses of various focal lengths had likely been used. The focal lengths, in turn, implied the necessary camera positions leading to their required interaxial distance in compliance with Wheatstone's simple instructions.

Perhaps the best demonstration of how the interaxial can be irrelevant while still producing good stereography is M. C. le Morvan's 3D image of the Moon. Published as an anaglyph[15] image on the pages of Illustrated London News on 8 March 1921. The hyperstereoscopic image had an interaxial of 28125 miles (45262.8 km), and the two exposures had to be taken about two years apart. Had the Moon been shot orthostereoscopically, it would appear as a flat disc, yet faithfully replicating human vision. It is the difference between doing things correctly or nicely.

Another overlooked aspect is the presentation. Even if the field of view of the stereoscopic image pair does not match the field of view of the photographic lenses, good stereoscopy is possible. Besides, this is a persistent case for

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[15] Anaglyph is a technique developed in the late 1800s by Louis Ducos du Hauron. Stereoscopic pairs are printed overlapping each other as one bi-colour image rather than two separate images. The left eye image is typically printed in red and the right eye image in cyan (complementary colour of red). Red-cyan glasses are then used to see the stereoscopic image in 3D. The technique has no relevance to virtual reality.

stereoscopic films. The field of view of the lenses and field of view of the audience both keep changing.

Wheatstone was a proponent of good stereoscopy. Insisting the main photographed object be on the convergence point. It is identical to James Cameron's style of stereoscopy used in the Avatar.

Brewster, on the other hand, strived for orthostereoscopy. However, not knowing this term, he used the expression "perfect representations".
Let's compare Brewster's rules with rules for orthostereoscopy side by side:

| **Brewster's Rules** | **Orthostereoscopy** |
| --- | --- |
| • Interaxial distance should equal to the average distance between eyes | • Captured with an interaxial equal to the human interocular distance |
| • The aperture of the lens should be equal to the aperture of the eye | • The camera lenses have the same field of view as the human eye |
| • The distance of the photographs in the stereoscope to the eyes must be equal to the focal distance of the camera lens | • The viewing angle of the image (or screen) is equal to the field of view of the lens |

Clearly, Brewster got it right only at the first point. His requirement of equal apertures is not relevant and is likely rooted in his understanding of photography and its technical possibilities in 1856.

## 2.6. Depth Cues

Stereopsis is the dominant mechanism making depth perception possible, but not the only one. Some depth information can be produced even by a single eye. Painting has a long history of depicting depth while having only a flat canvas to work with. Analogous are films, where single-lens images are projected on a flat screen, yet evoking a convincing sense of depth. Depth cues, in general, reinforce the depth perception conveyed by stereopsis, or step-in to convey depth if stereoscopic cues are not present.

### 2.6.1. Monoscopic Depth Cues

**Linear perspective** works hand in hand with relative size. If two objects of identical physical size are shown having different sizes on screen, the conclusion is that the smaller on-screen object is more distant. Conversely, if two real-world objects of different sizes, like a human and an elephant, share the same screen size, we assume that the human figure is closer.

**Texture scale** provides depth information based on the relative size of the texture. The relative size of a repetitive pattern, or even an irregular texture, will appear smaller with increasing distance.

**Occlusion** is the overlapping of two objects where one is behind the other. The partially hidden (occluded) object is perceived as the more distant one. Furthermore, the on-screen sizes of the objects in consideration play a role in the overall perception of their real scales. If an ape fully occludes a skyscraper, there are only two possible explanations. Either it is a giant ape, or the skyscraper is a scale model. This technique can be used only in conventional cinema or photography. Forced perspective, as the method is called, does not work in stereoscopy, because stereoscopic depth cues are superior to the monoscopic cues. The illusion of scale would fail. The same is true for virtual reality. Occlusion is not superior to stereoscopic depth and therefore cannot contradict it. It can only reinforce it.

**Atmospheric perspective** is a naturally occurring phenomenon commonly used in paintings, still photography as well as in motion picture photography. Water vapour and dust particles scattered in the atmosphere create a haze that gets thicker and more prominent with distance. As a result, distant objects appear to be softer and slightly blurred. They also lose contrast, saturation and have a slight blue colour shift[16]. Unlike occlusion, this effect can be used in VR to further emphasise the depth of a scene.

**Cast shadows and specular highlights** result from a light source — and the most natural source is the Sun. That has two implications. Firstly that it is just a single source, and secondly, that it is coming from above and usually at an angle, rarely from directly overhead. Therefore when looking at objects — their cast shadows and specular highlight positions — we evaluate their physical properties by assuming a single light source beaming from above. Simply put, lighting helps understand physical features. Lighting is a discipline that VR could vastly benefit from the expertise of cinematographers.

**Assumed shapes of known objects** determine how we interpret images of objects that we know. When we look at an image of an apple or tennis ball, we subconsciously assume the objects they resemble to be spherical and hence understand the images are depicting a spherical object.

All monoscopic cues work in static, as well as in moving images.

### 2.6.2. Motion-Based Depth Cues

Motion-based depth cues give off depth information when there is a change in position of the observer (or at least one of the objects) over time.

**Point of view motion parallax** is created by a head movement. As this causes a change in perspective, the perceived relative motion of objects offers information about their depth placement. Objects showing a larger relative displacement are closer than those which move less. The classic example is looking out of a side window from a moving vehicle — closer objects move faster than distant ones. Whenever we are not sure about the spatial relationships of

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[16] Air pollution in big cities make the haze brownish-yellow or gray.

objects, we instinctively move our heads sideways to reassure our assumptions are correct. It is an aid we very naturally and unconsciously use in day-to-day situations. Whenever this motion parallax does not work as expected in VR, the feeling of immersion takes a toll. That is the case of 360° VR that will be discussed later.

**Object motion parallax** reveals depth by comparing apparent speeds of moving objects. When watching a rowing competition from a riverbank, the boats closer to the observer seem to be moving faster than the more distant ones. Whenever there is a frame of reference, like a static background (the landscape), faster objects are evaluated as closer.

Films post-converted to S3D make use of depth cues extracted from motion-based parallaxes. Nevertheless, for static shots, it is necessary to create depth information, which is a complex process.

# 3. Stereoscopic Cinema and TV — a Prologue to VR

## 3.1. The Early Years

The Lumière brothers shot their famous Arrival of a Train at La Ciotat Station in 1895. It is less known that they shot a stereoscopic version of the film as well. There would be some uncertainty if it were in 1903 or 1935. Hayes dates it to 1903, claiming it "was released in France in 1903 but never shown theatrically in the U.S." [12] Clearly though, Louise Lumière had a deep interest in stereoscopy which he displays in Stereoscopy on the screen [13] published in 1936. The younger of the two brothers explains in detail his approach to the (red-green) anaglyph process, which is also how the stereoscopic arrival of the train was screened. Furthermore, he notes that during a stereoscopic projection, the screen appears to the spectator as an "open window and that the actors are moving within the very room." [13] The term stereoscopic window is still used in S3D cinema as a conceptual framework for thinking about the frame and the added depth perception.

Stereoscopic films developed alongside regular cinema right from the start, despite being overlooked by the history of traditional cinema. Though not produced in very high numbers, they still were interesting enough for early cinema entrepreneurs to construct stereoscopic cameras and experiment with various projection systems.

The first stereoscopic feature film — The Power of Love[17] — was released in 1922 and screened in anaglyph. That is 15 years before film met sound. The first S3D sound film, Zum Greifen Nah (Close Enough to Touch) was an insurance commercial shot in Dresden on Agfacolor reversal film stock. It premiered in Berlin on 17 May 1937. [10] The German army shot several training films during

[17] Dir. Nat G. Deverich, DOP Harry K. Fairall, USA.

World War 2. To do so, they used their own 35 mm stereoscopic camera system called Raumfilm-Verfahren. [10]

Another pioneer of this era was John Norling, who produced and directed a black and white S3D stop-motion film — In Tune with Tomorrow — for the Chrysler Corporation exhibit at the New York World's Fair in 1939. The audience was given polarising 3D glasses to view the film, which was projected on a silver screen by two synchronised projectors.

It was an era of rapid technological advancements, and filmmakers already had a profound understanding of stereoscopic filmmaking.

## 3.2. The Convergence Years

S3D films took Hollywood by storm in 1952. Bwana Devil[18] initiated a short but very intense wave of S3D films that faded away in 1955. In these three years, Hollywood released over 50 S3D feature films. Ray Zone calls this period the "Era of Convergence" because of filmmakers trying to mimic human sight and shooting converged (explained earlier). This phase gave birth to some iconic films like House of Wax[19], Dial M for Murder[20], or Revenge of the Creature (aka Return of the Creature from the Black Lagoon)[21].

The films were technologically quite mature. However, maturity would be a quality hard to defend when it comes to the aesthetics of stereoscopy. The 3D effect was more of a gimmick than a tool of artistic expression. It started with the opening credits demanding a place on the laps of the audience, often followed by the creatures. Objects poking out of the screen were the most favourite way of abusing stereoscopy in this period. The opening sequence of

[18] Dir. Arch Oboler & Robert Clampett, DOP Joseph F. Biroc and William D. Snyder, 1952.

[19] Dir. André De Toth, DOP Bert Glennon, J. Peverell Marley, Lothrop B. Worth, 1953.

[20] Dir. Alfred Hitchcock, DOP Robert Burks, 1954.

[21] Dir. Jack Arnold, DOP Charles S. Welbourne, 1955.

Revenge of the Creature could serve as a textbook example of how not to shoot S3D and cause an instant headache — exaggerated stereoscopy resulting in incorrect scale perception, window violations, or negative parallax abuse to name a few lapses.

Studios, as well as individual inventors, were developing their own (what we would now call) 3D camera rigs. Czechoslovakia was not just a by-watcher either. The camera manufacturer Josef Šlechta built a stereoscopic version of his famous "Šlechtovka" camera between 1952—1953. It can be seen in the National Technical Museum in Prague.

The surprisingly short life-span of the second wave was not caused by its poor aesthetics, but by a very different rival — Cinemascope. The early 1950s was a time when cinema was competing with television. Besides, both widescreen films, as well as stereoscopic films, were a cry for attention. Stereoscopic films at this time were shot and screened at the Academy aspect ratio (1.37) — exactly what widescreen films attacked. The winner was widescreen. Stereoscopy went silent for about 30 years.

## 3.3. IMAX and Immersion

The third wave came in the 1980s and was accompanied by a substantial change in screen size — IMAX. According to S3D film historian Ray Zone, "The film that announced the 'immersive' era of stereoscopic cinema and the giant screen was Transitions, a 1986 IMAX 3D film produced by Colin Low for Vancouver Expo" [10]. "Immersive era" because the IMAX screen is so large (up to 30 m wide) that one loses sight of the edges of the frame and feels being pulled in to the 3D image. This is close to the visual immersion VR offers, though not as extensive. The mid-1980s also happen to be a period when VR was making notable advancements.

## 3.4. The Digital Era

The fourth but first digital wave of stereoscopic cinema started quietly in 2005 with the 3D animated film Chicken Little, directed by Mark Dindal. A year earlier, another 3D animated film premiered — Polar Express[22]. Though it was shot digitally, it was still screened from two 70 mm print films. However, none of these films got much attention.

When James Cameron's Avatar took cinemas worldwide by a storm in 2009, stereoscopy was fully reborn, digitally. Nevertheless, this time, there were serious arguments why stereoscopy would be staying in cinemas for good. The first one was obvious — digital cameras, postproduction and screening. That made stereoscopy much easier to deal with. Like in the 1950s, various companies (e.g. 3ality Technica, P+S Technik, Cameron Pace) started manufacturing equipment for stereoscopic production, which made the shooting and (previously unthinkable) on-set monitoring, not just possible, but even quite comfortable. Intrigued by the potential and possibilities, more and more renowned directors ventured into shooting stereoscopic. That, in turn, fuelled enthusiasm about its viability.

James Cameron, together with stereographer Vince Pace, founded the Cameron Pace Group which produced stereo rigs used for shooting Avatar. It is not surprising that with such financial interests, Cameron issued strong statements about the future as he did for the BBC [1]. In the light of VR, it is questionable if Cameron meant films or entertainment in general, not excluding VR when he used the term "entertainment".

In the early 2010s, it seemed that S3D films would stay as a parallel line to the conventional cinema, though mostly limited to spectacular big-budget films as

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22 Dir. Robert Zemeckis, DOP Don Burgess ASC and Robert Presley, 2004.

Hugo[23], Life of Pi[24], Prometheus[25], The Hobbit[26], Gravity[27], World War Z[28], The Martian[29] and The Walk[30]. Though far from being a comprehensive list, there is an emerging trend in these mentioned films that reflect digital S3D filmmaking in the 2010s. Roughly in the middle of the decade, there is a departure form native stereoscopy — shooting with two cameras rigged together. It is replaced by post-conversion — a technique allowing to shoot with a single camera, without the hassle and bulkiness of a rig, leaving the making of the S3D image to postproduction. The results are not as impressive as in native stereoscopy, but good enough, even for blockbusters with high technical standards. Naturally, financial aspects played a role too, just as studio politics.

In many cases, films were planned and shot conventionally and by later executive decisions post-converted, sometimes without much consideration for the artistic implications. One infamous example is World War Z originally lensed by Robert Richardson. Paramount studios managed to upset cinematographer Robert Richardson to a point where he asked his name to be taken off the credits. [14]

On the other hand, it was also getting clear that filmmakers are starting to have a deep understanding of the technique. Now and then an aesthetically tasteful stereoscopic film appeared. The technique of stereoscopy was used consciously as a tool of artistic expression, as explained by Everest director and producer

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[23] Dir. Martin Scorsese, DOP Robert Richardson ASC, native stereo, 2011

[24] Dir. Ang Lee, DOP Claudio Miranda ASC, native stereo, 2012

[25] Dir. Ridley Scott, DOP Dariusz Wolski ASC, native stereo, 2012

[26] Dir. Peter Jackson, DOP Andrew Lesnie ASC, native stereo, 2012

[27] Dir. Alfonso Cuarón, DOP Rodrigo Prieto ASC AMC, post-converted, 2013

[28] Dir. Marc Forster, DOP Ben Seresin and Robert Richardson ASC (uncredited), post-converted, 2013

[29] Dir. Ridley Scott, DOP Dariusz Wolski ASC, post-converted, 2015

[30] Dir. Robert Zemeckis, DOP Dariusz Wolski ASC, post-converted, 2015

Baltasar Kormákur in [15]. Additionally, in rare cases, the stereoscopy was nothing short of poetic, like in the aforementioned mentioned Pina. Wim Wenders praised S3D as an evolution in film language. [15]

The most recent live-action films are post-converted, and native stereo is used mostly for 3D animated films. Setting up a second virtual camera is free of the real world restrictions and frustrations. In other cases, like Blade Runner 2049[31], promotion is not that eager as in the early 2010s to stress the film is even available in S3D.

## 3.5. 3D TV and Why It Failed

Stereoscopy was trying hard to become common in home entertainment too. "3D Ready" television sets were a matter of fact in the mid-2010s. Nevertheless, they were not a success for several reasons.

One reason is the long time favourite argument of glasses. They are necessary to see S3D, but people find them uncomfortable. Various TV brands used different technologies for the glasses, too — passive polarising glasses or active shutter glasses. Moreover, the glasses were only an implication of how the stereo-pair was displayed on the TV screens. In other words, a lack of standards and simplicity.

Using 3D viewing glasses leads to another complaint — dim images. Screen brightness was not compensated, and so watching S3D became a rather dark experience, especially under sub-optimal home viewing conditions. Furthermore, many people were happy to put on 3D glasses in the cinemas but reluctant to do so at home.

A limited offer of content was another deal-breaker. Live 3D TV was short-lived, like ESPN in the USA. It is no surprise considering the immense complexity of

[31] Dir. Denis Villeneuve, DOP Roger Deakins ASC, BSC, post-converted, 2017.

creating live S3D programmes. Watching recorded films required a Blu-ray player, as Blu-ray discs were the only medium of the time that supported S3D. With streaming platforms in the 2020s, this would become irrelevant. Netflix launched 3D streaming in 2012 and discontinued it shortly after because "3D viewing at home failed to captivate consumers". [16]

3DTV also ran into the chicken and egg problem. The USA underwent Digital TV Transition in June 2009. "Full-power television stations nationwide have been required to broadcast exclusively in a digital format." [17] This forced consumers with old analogue TVs to buy new digital sets. However, the transition to digital broadcasting came before most of the new TV sets had 3D capability. Eventually, when 3D arrived, households were not keen to buy yet another TV. "By 2015, just 9 per cent of US households owned TVs with 3-D capability, and by January 2017 all the major manufacturers had dropped the feature from their new models." [3] It was the worst possible timing for 3DTV.

Though S3D filmmaking was already mature by the early 2010s, it was new to TV. This infancy period meant "content was often created with immature systems by inexperienced creators, resulting in a great deal of poorly produced 3D content that alienated early adopters." [18] Bad stereoscopy, in turn, causes eye-strain and overall fatigue, further discouraging interest in it.

Another often mentioned aspect is stereo blindness — the inability to perceive depth by processing binocular disparity. A study on stereopsis and stereoblindness conducted on 150 MIT students discovered that up to about 4% of the test group were "unable to use the cue offered by disparity," [19] meaning that they are completely stereoblind. 10% of the test group had great difficulty properly assessing the depth of the given cues, making them partially stereoblind. The study states that up to 30% of the population suffers by some kind of inability to detect binocular disparity. [19]

Though stereoblindness is an objective medical condition, it remains debatable as a valid argument for or against the adoption of S3D. There always will be products or services not suitable for everyone and yet still be profitable. If stereo blindness were such an obstacle, it would hamper any development of any stereoscopy related technology from the stereoscope to virtual reality.

Concluding, 3DTV had an even shorter lifespan than S3D films for cinema. The marketing changed with the latest emerging technologies, and now the focus is on UHD, 4K, 8K and HDR.

## 3.6. Autostereoscopy

The many complaints about bothersome glasses looked upon autostereoscopy as the definitive answer to comfortable 3D viewing. Autostereoscopic displays do not require the viewer to wear a set of glasses. Instead, such displays work either using a parallax barrier or a field of lenticular lenses, either separating the left and right eye images respectively. A few such screens had been manufactured, but are not suitable for consumer use. The main technical limitation is narrow viewing angles, often restricting the use for just one person. Despite this technology being attractive for certain applications, it cannot be used in virtual reality due to physical constraints.

# 4. The Birth of VR

## 4.1. The Cinematic Approach

### 4.1.1. Cinema of the Future

In September 1955, just around the time when Hollywood's second wave of stereoscopic films was about to be over, Morton Leonard Heilig, a Hollywood cinematographer published Cinema of the Future [20]. A futuristic essay that laid one of the two foundations of virtual reality.

Heilig was influenced by the latest cinema systems challenging TV. Including immersive experiences like stereoscopic films and Cinerama — a (monoscopic) three-projector setup that projected films on a curved ultra wide screen big enough to cover the entire binocular field of vision.

However, Heilig was underwhelmed by these inventions and aimed further, at something much more mature and sophisticated. He criticised the flood of technical systems introduced by the film industry in the 1950s which promised revolutionary or similarly exaggerated experiences. The popular systems were too superficial for him. Heilig was deeply interested in a kind of storytelling that would overcome the limitations of linear narration. A form that could channel information, emotions and sensory perceptions of all kind — a combined art that could tap directly into all of it. In his own words: "Thus art is like a bridge connecting what man can do to what he can perceive." [20]

The essay is a vision of the evolution of cinema into an entirely new art form. Heilig was confident that it would be stereoscopic (or otherwise creating an illusion of depth) however not requiring glasses. He envisioned the images would be "electrically created," [20] "perfect in focus and stability," [20] and with no grain (a prediction of digital cinema). The sound would come from all directions, and air would be filled with odours. We would feel the "changes in temperature and the texture of things”. [20] Summing it up, the cinema of the future will let us “feel physically and mentally transported into a new world,” [20] just like VR does (or aims to do).

Heilig was aware that audiences could be overwhelmed by such an assault on all senses. Contemplating it, he writes: “The mastery of so many sense materials pose another problem — selection. People already complain about the excess of realism in films and say the new inventions shall plunge us from bad to worse.” [20] He argues that an artist must always strive to engage the audience as much as possible. “For without the active participation of the spectator there can be no transfer of consciousness, no art. Thus art is never ‘too’ realistic.” [20]

In this sense, realism is still not a guarantor of consciousness transfer, as Heilig wishes. His argumentation implies one, solid and commonly shared reality coming through sensory input. Two people observing the same object or event simultaneously, be it in a film scene, or in real life, do not necessarily have the same perception of such a “reality”. Therefore it would be more accurate to talk about transferring or conveying an impression or viewpoint, rather than consciousness. Such impressions are only a collection of aspects of the greater whole, observed by the observer creating individual perceptions of reality. The reason why consciousness cannot be transferred can be traced to Heilig’s idea of consciousness itself.

Cinema of the Future is portrayed as an art form that, once when all technical obstacles would be overcome, will combine the senses of sight, sound, smell, taste and touch. “These elements are the building bricks, which when united create the sensual form of man’s consciousness, and the science of art must devote itself to inventing techniques for recording and projecting them in their entirety,” [20] Heilig explains. The emphasis on the word sensual is important. Heilig explicitly rejects any kind of internal mental states having a connection to consciousness, and therefore they have no place in the cinema of the future. He further envisions "… the cinema of the future will no longer be a 'visual art,' but an 'art of consciousness.'" [20]

Heilig's notion of consciousness is purely sensory, and in effect, materialistic. Nevertheless, it is a close (though reduced) concept of consciousness in Buddhist philosophy, which sees consciousness as a natural phenomenon that constantly arises and ceases depending on the awareness of sensory objects. These sensory objects are sight, sound, taste, smell, touch and mental formations (e.g. volition, concentration, attention, thinking, compassion, joy, greed, or hate). Sensory objects come through sense organs — eyes, ears, tongue, nose, body and the mind[32]. Sensory and mental consciousness is the whole of human experience. There is no pure consciousness. It is not a stand-alone entity. It always must have an object to arise and therefore is interdependent.

This concept will be used as a framework and reference in further discussions about VR. It will help examine the possibilities and limits of virtual reality from a broader perspective, as such a thought mode is close to the author's inclination.

### 4.1.2. Sensorama

The cinematographer and visionary did not stop with an essay. Two years after publishing it, he built a multi-sensory cinematic machine, the Sensorama. It is widely considered to be the first functional multi-sensory, or shall we say, immersive device and the first glimpse of a virtual reality device. Heilig was granted a patent for the Sensorama in 1962. [21] He had also built a 35 mm stereoscopic camera rig for shooting films for the Sensorama, making a complete ecosystem for his vision.

[32] The mind is considered a sense organ too, capable of sensing abstract objects (mind objects).

The Sensorama was a single person viewing device resembling an arcade video game machine of the 1980s, or a Kinetoscope with a seat. It came with five short multi-sensory films, such as a motorcycle ride through the streets of New York or a helicopter ride. The machine was faithful to the traditions of early cinema, and one had to insert a token (coin) to see a show, like with a Nickelodeon. It even had motorbike-like handles to hold on to.

In a short video interview conducted in December 2010 [22], the inventor explains that the device has 3D peripheral vision, stereophonic sound and that it can blow air against the hands and feet of the person seated at the apparatus. The seat is a means of sensory input too as it vibrates. Each film used two smells to satisfy the olfactory dimension of the experience. However, the machine itself could contain up to 10 smells.

The nature of the Sensorama was not interactive. Heilig constructed it as a new-form-of-cinema device which would only playback predetermined performances. Nevertheless, right from the beginning, Heilig wanted his invention to be eventually used simultaneously by one or more persons "to experience a simulated situation." [21] He intended to refine the device to "provide a new and improved apparatus to develop realism in a simulated situation," [21] aiming towards what would become virtual reality.

Entertainment was only one of the uses for the Sensorama. Heilig was aware of the educational and training potential of it. In the patent itself, he describes how the device could be used to explain complex ideas or train industrial workers and military personnel in dangerous procedures without risking their health or lives.

Regardless of how crude or imperfect the Sensorama looks like today, this invention is why Heilig is often considered the father of virtual reality.

### 4.1.3. Telesphere Mask

Morton Heilig invented another VR-like device. The Telesphere mask (patented in 1960 as Stereoscopic-television apparatus for individual use [23]) was the first head-mounted display (HMD) created. However, without any head-motion tracking, it was not interactive either. One could watch stereoscopic films with stereophonic sound and feel a breeze thanks to a pair of air nozzles, which could blow perfumed air as well. The whole contraption was adjustable for comfortable wearing, the patent states.

The screens were made of two miniature television tubes optically adjusted so that they create a "sensation of peripheral vision filling an arc of more than 140° horizontally and vertically." [23] Such a field of view is remarkable even by today's standards of VR headsets.

The Telesphere mask was ahead of its time and had no success. Morton Heilig invented a few more immersive devices and systems (e.g. Thrillerrama) as well as some sports training devices. He passed away in 1997 at the age of 70 before seeing his dreams reborn as 360° videos.

## 4.2. Computer Generated Virtual Worlds

### 4.2.1. The Ultimate Display

The second method of putting someone in an artificial or simulated environment is by forging a completely new world. No cinema, no complicated camera rigs, nothing real at all, but generating all sensory input by computer. This idea was first proposed in 1965 by Harvard University professor Ivan Sutherland[33] in The Ultimate Display. [24]

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[33] Ivan Sutherland lay the foundations of computer graphics and computer aided design (CAD) in his 1963 PhD Thesis software Sketchpad.

When Sutherland wrote the two-page paper, available computer displays (cathode ray tubes) were limited to displaying text and drawing lines. The paper is an extrapolation of Sketchpad[34]. An examination of what a computer display could do to give visual feedback to the user about objects unfamiliar from the physical world, proposing it could become a "looking glass into a mathematical wonderland". [24] The idea is quickly extended, and Sutherland suggests that such a looking glass "should serve as many senses as possible." [24]

Sutherland anticipates The Ultimate Display as "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." [24] It is truly the ultimate immersion one could experience. Although such a device so far exists only as a holodeck in the Star Trek TV series, Sutherland predicted several technologies and innovations that would become inseparable with today's VR.

One of those technologies was gesture-based controls that we mostly associate with smartphones and tablets today. Sutherland's Sketchpad already had used a flick of the hand gesture to indicate the end of drawing a line. Eye-tracking was shortly mentioned in the Ultimate Display too: "For instance, imagine a triangle so built that whichever corner of it you look at becomes rounded. What would such a triangle look like? Such experiments will lead not only to new methods of controlling machines, but also to interesting understandings of the mechanisms of vision." [24] Changing the appearance of an observed object (or area of the image) is a technique proposed in foveated rendering discussed later.

[34] Sketchpad was a computer graphics programme written by Sutherland as a part of his PhD Thesis at MIT. It is widely considered the predecessor of today's CAD (Computer-aided design) programmes.

The closest technology to a holodeck (and The Ultimate Display) is a CAVE [25], an acronym for Cave automatic virtual environment — a room-sized VR environment inspired by The Ultimate Display. The walls of the room display images that can be seen by a viewer inside the room equipped with motion-tracked 3D glasses. The images change according to the viewers' position, creating an illusion of immersion for the viewer, who can freely walk around in the physical room. The imagery can be created by rear projectors (as initially suggested in [25]) or large-scale flat panels. "CAVEs were invented by Carolina Cruz-Neira when she was a student of Dan Sandin and Tom DeFanti at the University of Illinois." [4]

### 4.2.2. The Sword of Damocles

In 1968 Sutherland constructed a head-mounted display. It could not claim primacy, that credit goes to Morton Heilig's Telesphere Mask, but Sutherland's HMD was a first in a different way. It showed stereoscopic images of a computer-generated world, or as Sutherland called it — a virtual world[35] — using a pair of miniature cathode-ray tubes. The objects of this world, however, could only be wireframe drawings. Rendering opaque objects were beyond the reach of the computers available to date.

The headset, or more precisely, the pair of goggles, were attached to a ceiling-suspended arm that took care of head-motion tracking — another technology introduced in The Ultimate Display — a feature vital for virtual reality. This allowed the user to "move his head three feet off axis in any direction to get a better view of nearby objects." [26] The user could turn around to look at what is

[35] The term "virtual world" is sometimes attributed to philosopher of art Susanne Langer, who used the terms "virtual-" (-space, -character, -object, etc.) when discussing various art forms in her 1953 book Feeling and Form. Nevertheless her use of the term "virtual world" referred to a virtual world of e.g. characters in story. It has no connection to our understanding of VR.

behind him and also slightly tilt his head up or down. Sutherland stressed the importance of such interaction and change in viewing perspective: "Although stereo presentation is important to the three-dimensional illusion, it is less important than the change that takes place in the image when the observer moves his head." [26]

This is arguably one of the most important findings in VR. If you want to feel immersed, to be inside a virtual world, the world itself must respond as you would expect. "Input is more important than display. Your input in VR is you." [4] Sutherland and his team wanted to further develop the whole system, so the user could freely walk around in a room without being restrained by the head-motion tracking system. This is known as six degrees of freedom (translation and rotation in all 3 axes) in VR.

Sutherland's goggles were fitted with semi-transparent mirrors (beam splitters) that enabled the wearer to simultaneously see the virtual objects and the real physical space. The displayed virtual objects could be aligned with a physical object in the room (like a map, wall or typewriter keys as Sutherland suggests), or they could simply float in space. [26] This concept was ahead of its time too. It is now known as augmented or mixed reality (AR or MR) and will be discussed later.

A key requirement for convincing and pleasant AR/MR is orthostereoscopy. Sutherland's goggles could be mechanically adjusted to fit varying interocular distances of different users. The stereoscopic image too, could be tuned in terms of the virtual interaxial distances (called "virtual eye separation" in [26]). This naturally led to users consistently reporting very good and realistic stereoscopy, although the image was not strictly speaking orthostereoscopic. The user had a field of view of only about 40°, which is hardly enough to contain the human field of view. However, the goggles rendered an overlay image that matched the perspective of the physical world — that produced very good stereoscopy, though not orthostereoscopy. Sutherland was very pleased about this realistic perception, but surprisingly he never mentions orthostereoscopy in his either of his papers [24; 26].

Sutherland's HMD is sometimes wrongly called The Sword of Damocles, which was the intimidating arm-like device that held the goggles from the ceiling.

## 4.3. VPL Research

1984 was a significant year in technology. Apple revealed the Macintosh computer and VPL Research[36] was founded. The two companies had more in common that it would appear at first sight. Some of the early VR demos at VPL were coded by Andy Herzfeld, a then fresh ex-employee of Apple, "who had written the Macintosh operating system." [4] Though VPL did considerable progress in virtual reality, it was short lived. The company filed for bankruptcy and "was acquired in 1999 by Sun Microsystems, which eventually became part of Oracle." [4]

### 4.3.1. Jaron Lanier

The key figure and founder of VPL *Research* was a visionary, computer scientist, composer and visual artist — Jaron Lanier. Lanier's parents were Jewish. His mother Lillian was a concentration camp survivor from Vienna, and his father's family fled from Ukraine in fear of the pogroms. Young Jaron lived very humbly with his parents in a remote area in El Paso, close to the Mexican border. His mother insisted he went to school in Mexico because the schools there were better than in the US. When Jaron Lanier was 9, his mother was killed in a car crash, and his father Ellery was badly injured. Misfortune followed as Jaron had to spend about a year in the hospital. When he was finally released, the house

[36] VPL stands for Virtual Programming Languages.

his father just bought burned down. They were left broke. Ellery Lanier, with the little money left, "bought an acre of throwaway land in New Mexico," to rebuild a very modest life. [4]

The father and son lived on the property in tents for a few years. Ellery Lanier was an architect, so after saving some money, he started building a house of geodesic domes. Jaron, who was about 13 at the time, was entrusted by his father to design his own room. They called their home the Dome. Jaron Lanier moved out eventually, but his father lived in there "into his late eighties, when he couldn't live independently anymore." [4]

This is just a glimpse into the extraordinary life of one of the most influential people in VR, as well as the author of the term virtual reality. In Lanier's own words: "I wish I could remember the precise moment when I started using the term 'virtual reality.' It was in the 1970s, before I came to Silicon Valley, and it served as both my North Star and my fledgling calling card." [4]

Lanier left VPL before it went bankrupt. According to him, the company stopped innovating, which ultimately led to its downfall. Currently, he works for Microsoft at a position called the octopus "(Office of the Chief Technology Officer Prime Unifying Scientist)." [27]

Lanier is "widely considered one of the foremost theorists of the impact of technology — and particularly the Internet — on society, Lanier was named to TIME's 2010 list of the 100 most influential people in the world." [28]

#### 4.3.2. EyePhones, DataGloves and DataSuits

VPL was the first company to sell commercial VR products. Namely the EyePhone headset with head-motion tracking, the DataGlove for haptic feedback when touching virtual objects, and its flagship product, the RB2. The RB2 (Reality Built for Two) was a complete virtual reality system that could bring in more than two people into VR simultaneously. They would see each other as avatars. The system cost „in the millions of dollars. The biggest and most expensive parts of the RB2 were the computers, usually from Silicon Graphics, as big as refrigerators.” [4]

„In the earliest experiments with networked virtual reality, each person would appear inside the simulation as a floating head and hand only.” [4] As computing power increased, the company started working on a full-body outfit called the DataSuit. It measured movements of the arms, legs and the body. The motivation behind the DataSuite was to enable full interaction of two people in networked VR. DataSuits were, in fact, motion capture suits, and probably the first ones to be sold. [4]

Lanier recalls that one of VPL's first best-selling VR application was a kitchen design tool. "This was a collaboration with the giant industrial conglomerate Matsushita, and the VR experience was set up in a high-end kitchen showroom in Tokyo." [4] As VR was a state of the art technology, the price tags for the remodelled kitchens were far from average. Surprisingly though, „The hardest problem was modifying EyePhones so that they wouldn't mess up the expensive hairdos of women," [4] which was not considered too interesting by the VPL engineers.

Cities were other notable customers of VPL. "We helped Singapore plan for its spectacular growth by building a model inspired by the virtual Seattle (…). We helped the city of Berlin plan restorations after the wall fell, in collaboration with wonderful research teams from German universities and our German partner ART+COM. These renderings of Berlin were, I believe, the first virtual worlds with real-time shadows and reflections." [4]

## 4.4. Into the Mainstream

Virtual reality started making appearances outside the Silicon Valley circles in the early 1990s. The widely accepted notion is that VR went mainstream with The Lawnmower Man[37]. A sci-fi horror film base on a Stephen King novel. Pierce Brosnan played a character called Dr Lawrence Angelo, who was inspired by Jaron Lanier and his work. The film thematised virtual reality as a technology with all the VR gadgets of the time, and fabulated a bit further, as it was a science fiction film.

However, the idea of a virtual environment with the full freedom of movement came a few years earlier into pop-culture. The TV series Star Trek: The Next Generation introduced the Holodeck, a device which provided full sensory stimulation and full freedom of movement. Of course, being true to the sci-fi genre, the holodeck is more a dream of what VR could become one fine day. The first appearance of the holodeck in the series was in 1988. [29]

The electronic toymaker Sega released a VR headset with LCD screens, head-motion tracking and stereophonic sound. However, it was not commercially successful. [30]

Nevertheless, the media reported enthusiastically about VR: "We are witnessing the birth of Virtual Reality — the total electronic environment which will change our perception of the real world as surely as books or television." [31] In January 1995, Newsweek magazine reported about the CES[38] in Las Vegas: "virtual reality is finally coming to the living room." [32]

The blockbuster film The Matrix[39] refreshed the concept of virtual reality for broader audiences. It depicted humans as an enslaved species being kept alive

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[37] Dir. Brett Leonard, DOP Russell Carpenter ASC, 1992.

[38] Consumer Electronics Show

[39] Dir. the Wachowski siblings, DOP Bill Pope, 1999.

and bred in a simulation of reality. As much as the film (and its sequels) created ripples in filmmaking and culture, it did not even make a dent in the development of VR as a technology. Besides, nobody would want to live in anything close to that kind of a simulation anyway.

Just like with stereoscopic films, people lost interest in VR. None of the commercially available VR systems in the 1990s were good enough, and VR disappeared from the public's eyes.

20th century VR was for geeks, technological enthusiasts and a very narrow segment of professionals who used it for training and simulation purposes. NASA has been using VR for astronaut training since 1990. They developed the Virtual Interface Environment Workstation (VIEW) — a stereoscopic HMD with a DataGlove that enabled the astronaut trainee to interact with the virtual environment. VIEW was developed in partnership with VPL Research. [33]

# 5. The Rebirth of VR

During an early stage of a new technological turn, or while just “sensing” the imminent change, the tendency to universalise its novelty and assume that from now on it will completely dominate all human activity is common.

— Stanisław Lem [34]

## 5.1. Oculus Rift

VR made a grand comeback in 2012. And just as in the past, it was driven by pure enthusiasm. On 15 April 2012, Palmer Luckey, a 19 year old gaming and VR fan posted a help request on MTBS3D forums [35] about a low latency, high resolution, and 110° horizontal field of view[40] HMD VR kit he was developing. He claimed it was the “first truly immersive virtual reality headset for video games,” [36] and asked for assistance with a Kickstarter crowdfunding campaign. The campaign started the same year on 1 June with a goal to collect $250,000 to complete the HMD — The Rift. Luckey promised to ship *The Rift* as soon as possible after the campaign ended. A month later, 9522 people contributed to the project and collected $2,437,429. [36]

As for the early shipping, the plan did not work as intended, and Luckey could not keep his word. The Oculus VR online store took first orders for The Rift on 6 January 2016. [3]

## 5.2. 2 Billion Dollars of Motivation

Before Oculus VR sold a single Rift unit, it managed to make headlines in respected media (BBC [37], CNN [38], The Guardian [39] etc.). Social media

[40] The Telesphere Mask had a 140° horizontal and vertical field of view.

was buzzing too, and the biggest one of them all was the cause. On 25 March 2014, Facebook announced that it would acquire Oculus VR for $2 billion. [40]

In the reasoning, Facebook stated that Oculus VR had already received over 75,000 orders for the headset and that applications for VR are far and wide, though not yet quite mature for anything else than gaming. Facebook wanted to take advantage and use VR in "communications, media and entertainment, education and other areas." [40] The social media company made it clear that they see VR as "the next social and communications platform." [40]

However, this is a very different vision of a social VR in contrast to what Jaron Lanier imagined much earlier: "I was immediately obsessed with the potential for multiple people to share such a place, and to achieve a new type of consensus reality, and it seemed to me that a 'social version' of the virtual world would have to be called virtual reality." [4] Lanier's VR is a consensus reality, a concept that social networks do not even consider, as it contradicts their objectives and outcomes alike (discussed later).

If you want to understand the state of VR today, follow the money. Facebook spending $2 billion on VR sent a message that VR must be the unequivocal "next big thing". Therefore, with a pinch of cynicism, the hope of making big money was the driving force behind the VR revival in the past few years. The VR movement was no longer in the hands of dreamers who wanted to transfer consciousness, brilliant non-conform inventors fascinated by the medium itself, or enthusiasts wanting to immerse in computer games, but in the clutches of giant technological companies working to make a profit.

The optimism that VR would finally work spread quickly. There was no shortage of fantastic claims about how everything would be ground-breaking, mind-bending, better than ever, revolutionary and game-changing. "Make no mistake about it: VR won't just change our leisure time. It will change our very culture." [41] Claims very much like the overstated advertising of the 1950s that Morton Heilig disliked.

## 5.3. Sony and Google Jump on the Bandwagon

Just a few days before Facebook made its intentions about VR public, Sony introduced Project Morpheus [42], its own prototype VR system that works with its PlayStation 4 video game console. The company revealed that they had been working on the project for over three years. The prototype headset offered 1080p resolution, a 90° field of view and head-motion tracking. Additionally, it boasted 3D sound as well.

In June 2014 Google unveils Google Cardboard[41]. [43] A low-cost do-it-yourself cardboard VR headset intended as an entry-level VR viewer of other Google products like Google Maps or YouTube. Slide an Android smartphone in the Cardboard and, once worn, one has an elementary VR headset. The smartphone sensors (accelerometers and gyroscopes) take care of the head-motion tracking with a relatively low-latency. No extra computers required, with no attached cables.

The Cardboard viewer was seen as a mockery of the Facebook-Oculus deal. $2 billion for having only a prototype in development on one side and a crude piece of cardboard fitted with two simple lenses, and a rubber band to hold a smartphone in place offering simple VR on the other side. That was how the (social) media responded to the project.

## 5.4. New Storytelling Attempts

### 5.4.1. The Daily 360

In November 2015, The New York Times distributed a Google Cardboard viewer to "all domestic New York Times home delivery subscribers who receive the

[41] https://arvr.google.com/cardboard/

Sunday edition." [44] Alongside with the goggles, the newspaper released three documentary 360° VR videos about war-displaced children. The series was titled The Displaced. To watch the short videos, one had to download a free viewing app for Apple and Android phones. The 360°s can additionally be watched on YouTube[42] with or without a VR headset.

The article's title was "NYT VR: How to Experience a New Form of Storytelling From The Times." Again we are witnessing the excitement over new technology. This time, VR is seen as a new form of storytelling for journalism. In the words of Jake Silverstein, editor of the New York Times Magazine: "This new filmmaking technology enables an uncanny feeling of connection with people whose lives are far from our own." [44]

The distribution of the Cardboard viewer started a section in the newspaper called *The Daily 360*. The New York Times had published 301 monoscopic 360° VR videos on its YouTube channel[43]. Clips viewable with a VR headset or without, spanned from under a minute up to 12 minutes. The channel was last updated on 4 July 2018. After that day, not a single VR 360° video had been released.

### 5.4.2. Oculus Story Studio

Oculus Story Studio was founded as a division of Oculus VR, that was supposed to produce animated films for VR. The ten-person team was led by Saschka Unseld (Creative Director) and Max Planck (Supervising Technical Director), both "directors from Pixar Animation Studios." [3] Other professionals from DreamWorks and Industrial Light & Magic were part of the team too. Story Studio planned to release 5 films in 2014 — each one to explore a different genre.

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[42] https://youtu.be/ecavbpCuvkI

[43] https://youtube.com/playlist?list=PL4CGYNsoW2iCGZa3_Pes8LP_jQ_GPTW8w

Edwards Staachi, Producer, Oculus Story Studio admitted that everyone on the team was learning to tell stories in VR and that the method was trial and error. [45] The language of VR was being discovered on the run.

The paradox was that Story Studio was developing films designed for The Rift headset before Oculus VR sold a single Rift. It is a way, though, how not to run into the chicken and egg situation. However, the plan dit not work out.

Instead of five announced animated films, the studio produced three — Lost, Henry, and Dear Anjelica. Henry won an Emmy in 2016 for Outstanding Original Interactive Program, and Dear Anjelica was in the official selection of the 2017 Sundance festival. Despite the limelight, in May 2017, Story Studio in a blog post with corporately sanitised language announced that they would be shutting down operations. [46] Gone was the enthusiasm for learning the grammar of VR storytelling. Instead, the strategy covertly changed and Facebook, Story Studio's owner, decided to take a different approach on VR — far from storytelling and closer to the company's most popular product.

# 6. 360° VR

Not all VR is created equal. Contemporary VR walks in the footsteps of its historical prototypes. Leaving some of the original baggage behind and picking up some new along the way.

One of the existing lineages is 360° VR — also known as VR 360, 360° video, and sometimes spherical video. 360° video is a particular use case of VR. It uses either a specialised 360° camera or a rig containing multiple cameras. In both cases, the individually recorded images must later be stitched together to form the inside of an illusory sphere that can be viewed in a VR headset. Stitching is a technical term used to describe the postproduction process of joining the separate images into one seamless sphere that would conceal the overlapping parts.

However, not all 360° VR must be video. The spherical image can likewise be entirely artificial, like a 3D rendering. Invariably, 360° VR presents a static or dynamic spherical image through a virtual reality headset. When viewed, one has the feeling of being in the middle of a scene, or inside it. The image can be monoscopic as well as stereoscopic. However, it is most commonly monoscopic due to the many technical challenges of a seamless stereoscopic stitch. Additionally, 360° videos can be viewed on regular computer screens. Nevertheless, one can freely change the angle of gaze to enjoy a windowed view into the sphere, which naturally is not as immersive.

The ancestor of this branch is Morton Heilig’s Sensorama and Telesphere Mask. Ironically, all of Heilig’s content on these devices was stereoscopic.

## 6.1. Temptation of Cinema

The similarity of spherical video with films is very seductive. It misleads many to believe that it is a (new) form of cinema or new technology which can be used for filmmaking in the narrative sense. Spherical video is tempting to be treated like film and even used for storytelling like film. Though he was far ahead of his time with the Telesphere Mask, Morton Heilig thought too, that this form would be a new form of cinema.

### 6.1.1. Immersive Impressions by Journalists

The New York Times fell for it and struggled for over two years to try to make use of spherical video in journalism. They were hoping that it would be (or become) a new way of storytelling (note the shift in meaning from reporting) for journalists. Eventually, they gave up. The videos did not have any notable progress or evolution in form.

The 360°s were short clips with a few camera positions, and occasionally some text added — only an informative glimpse into some situation. The more ambitious ones attempted to tell a story like The Fight for Fallujah [47]. However, those hopes had to be accompanied by the voice of a narrator. Without the voice, the 360° video made hardly any sense as a story. The only notable difference was the shooting style — the camera tended to be in the middle of a group of people (or action), putting the viewer in a good position to see as much as possible, but in a questionable perspective in respect to the covered story.

The BBC has its 360° YouTube channel too [48], with 46 short videos. Their form is not too dissimilar to the production of the New York Times. The first video was posted in 2015, and the last one on 19 April 2019.

The National Geographic has some mostly nature-oriented spherical videos. Neither they have found a novel way to use this technical feature, besides being an attraction.

### 6.1.2. An Artist Observes

Happiness and Sadness Always Coexist is Ai Weiwei's first artwork created in virtual reality. It consists of two roughly 25 minute long films — Displaced Working Elephants in Myanmar and Rohingya Refugees in Bangladesh. Both shot as 360° video.

Both pieces are recordings of unscripted events unfolding. Several minutes long takes joined together. The intention was likely to offer an immersive, contemplative time spent with gentle and intelligent animals abandoned by their human owners and refugees rejected in their country because they are an ethnic minority — showing the similarities of suffering sentient beings. Both fates, human and animal, are saddening. However, VR plays no role in making this feeling come across any more than it would in a conventional recording of the same situations.

Despite the decent technical quality of Ai Weiwei's spherical video, it does not compensate for the inadequacy of storytelling. The viewer is again cast in the middle of something happening and left clueless. After a while of observing, curiosity takes over, and one starts to look around — sometimes at a dramaless scenery, sometimes at some other action. Then a cut interrupts the viewers' effort to make sense of the scene. The camera positions do not seem to be thought through, which leads to awkward perspectives for an immersive experience. Who is the observer, is the obvious question, when the camera hangs in mid-air higher than an elephant. In another instance, the camera is placed on a table where administrative work is being done. What is the idea of such a shot? What emotion is it supposed to communicate? Moments like these raise doubts about the motivation of such camera positions and the overall storytelling intentions.

This 360° attempt leads to more frustration than feelings of sympathy towards fellow human beings and animals. The hope of technology automatically conveying emotions is more evident than the story, just as the lack of narrative form.

### 6.1.3. Interactive Animated Films

When Oculus Story Studio started flirting with animated VR films, Nate Mitchel, its Co-Founder, admitted: "No one knows, what the language, what the grammar of VR storytelling is." [45] Unlike others though, Oculus Story Studio wanted to make the films interactive. Virtual characters would react when looked at. However, that can only take the endeavour of finding a language for VR storytelling away from a linear narration.

Their departure from the venture suggests that neither a team of professionals from Pixar, DreamWorks and Industrial Light & Magic could find the language or grammar.

"Every Hollywood studio you can imagine — 21st Century Fox, Paramount, Warner Bros. — has already invested in virtual reality. They've made VR experiences based on their own movies, like Interstellar[44] or Ghost in the Shell[45], and they've invested in other VR companies. Hollywood directors like Doug Liman (Edge of Tomorrow[46]) and Robert Stromberg[47] (Maleficent[48]) have taken on VR projects." [41]

[44] Dir. Christopher Nolan, DOP Hoyte van Hoytema ASC, FSF, NSC, 2014.

[45] Dir. Rupert Sanders, DOP Jess Hall ASC, BSC, 2017.

[46] Dir. Doug Liman, DOP Dion Beebe ACS, ASC, 2014.

[47] Stromberg was involved with Oculus Story Studio.

[48] Dir. Robert Stromberg, DOP Dean Semler ACS, ASC 2014.

#### 6.1.4. Filmmakers Explore

Professional filmmakers not affiliated with the big studios experimented with VR films on a smaller scale too. One example is Ashe '68[49], a seven-minute VR film that plays with mixing archival footage, sand animation and 360° footage. The cinematographer, Eve Cohen, combined various cameras to shoot different 360° scenes in the film. Including a unibody 360° camera and a Canon C700 with a 4.3 mm fisheye lens. [49] With the fisheye lens, Cohen split the shot into two takes. One take in the direction of the main action and the other take in the opposite direction. As the lens had a 250° field of view, both shots overlapped well and could be stitched in postproduction, creating a full sphere. This approach enabled her to tackle lighting elegantly, as she did not need to hide the lights from the all-revealing 360° view. Nevertheless, the shots had to be always static. Ashe '68 was not Cohen's first VR film, so she explains another paradox in 360° video — the non-existent frame. In her view, "It's just thinking of the world around you as a sphere instead of a rectangle. We don't have to frame it, and you can use the whole space." [49]

The film is more of a visual experiment for a VR headset than a purebred short. The live-action shots make only a small part of the 7 minutes. Most of the film is sand animation and archival footage. The sand animation is treated as a 360° image, which is undoubtedly original and beautiful. The archival footage is embedded into the sphere with abstract and non-distracting moving texture surrounding it. This makes it easy to watch as it becomes a framed screen in the viewing sphere.

The sand animations follow the paradigm of placing the camera (in this case, the effect of a virtual camera created in postproduction) in the physical middle of the scenes. That makes the action hard to watch because it takes a while to realise

[49] Dir. Brad Lichtenstein, DOP Eve Cohen, 2018.

that the animations are 360°. One can easily miss something important in the story because of looking in another direction. In effect, the story can become confusing.

## 6.2. Breaking the Frame

Cinema paints on a defined rectangular screen. Confining images within a frame is a natural way for us to see and create images. The frame itself is an important element and lead to our attention. We understand that what is within is important for the story. Violating this paradigm leads to questions that anybody attempting to create in 360° will inevitably have to confront.

### 6.2.1. Shot Sizes

The frame itself is a tool, not a constraint. What is within the frame can be equally important as what lies beyond it. What is within is the conscious and known. In contrast, what lies beyond is a mystery and the unknown.

Breaking the frame leads to the impossibility of shot sizes — an essential tool of film language.

A close-up with a longer lens is technically impossible because of the nature of spherical video. What remains is to bring the camera closer to the subject. That does not create the desired result either. Firstly, the portrayal of a face with a wide-angle lens is unflattering. Secondly, the nature of 360° video makes it impossible to get too close to a subject because of revealing stitch lines. Additionally, if the image were stereoscopic, there would be a minimum distance of the subject from the camera. Violating this distance would result in too large horizontal disparities, that in effect would be too painful to fuse.

The solution to the first problem would have to be a massive rig with many standard focal lenses that would cover the entire sphere. That would, in turn, create many more stitch lines to deal with and the imaginary sphere of projection would become even bigger, pushing back the possibility of getting close to a subject even further. Additionally, photographic issues, such as close focus distance increasing and depth of field decreasing, would come into effect. Since a shallow depth of field is undesirable in spherical video, neither is this a solution. Moreover, shot sizes require a frame as a reference of scale.

Therefore whatever attempt to bring the camera closer to the subject is technically and aesthetically unpleasing. As a result, shot sizes are not achievable in 360° video — they are a tool we cannot use.

Without shot sizes, without close-ups more precisely, possibilities are scarce to communicate facial expressions and emotions. With no emotions, there is no connection to characters. Immersion alone, as a feeling of being physically present somewhere, is not enough to convey happiness, sadness, fear, or other emotions.

There is a stark difference between being somewhere physically, simulating that experience, feeling peoples' emotions, and conveying them to an audience through any media. Such confidence in the immersive power of VR suggests a poor understanding of film language and image perception and interpretation.

### 6.2.2. Movement

Motion sickness is caused by a conflict between the visual and vestibular systems. It happens either when motion is seen but not felt, felt but not seen, or when the two perceptions do not correspond. In VR, all three cases can happen.

When you watch a 360° video, the only expected head movement is rotation — you can look around. However, if you move your head sideways and expect a change of perspective, that will not happen. The same applies if you stand up or lower your head. The perspective of the image will remain unchanged. This is not only a huge disappointment to many but also a potential cause of motion sickness. If such moments are not too frequent or too long, it should not be a concern. If the viewpoint does not change as expected, the viewer gives up anyway. However, a great deal of the immersion is gone, and nobody is likely to make oneself nauseous willingly.

When the camera moves and the viewer remains still is a more complex situation. Slow camera moves tend to be acceptable, while fast and erratic movement is likely to cause discomfort. Camera movement combined with head movement (like bobbing your head sideways) is very likely to make one feel sick after some time.

There is one technical aspect of VR that is specific to the medium — latency. It is the time between ones (head) movement and the expected reaction of the image one sees in the headset. In other words, the delay of the world reacting to your movement, your input, you. „Visual experience is based on integrating all you've seen and anticipating what you'll see next. The brain sees more than the eyes do." [4]

Low latency is crucial for good VR because it prevents motion sickness. Nevertheless, it is not a magic bullet that will guarantee success to VR. Sadly, this technological aspect had been overestimated in the early stages of the 2010s VR rebirth. After seeing impressive technical demos with new headsets like the Oculus Rift, many believed that VR would finally make a breakthrough because latency was no longer an issue. They narrowed the medium to its technical aspects. In the words of Pixar co-founder Edwin Catmull: "Now with Oculus they're saying there's a new storytelling medium. All that the new virtual-reality stuff did was they removed the time-lag, because it was the time-lag that made you feel that you weren't in the environment." [50]

### 6.2.3. Editing

Editing proves to be problematic in 360° VR as well. It goes back to the problem of the non-existing frame and attention guiding. When one is, so to say, inside a scene, it is natural to look around. However, when nothing (or nobody) is directing attention, one likely looks somewhere else where there might be nothing relevant to the unfolding events. At this moment, a cut can be quite disorienting because connecting two shots in the cinematic sense does not work as expected and eventually is not achievable.

The subsequent shot must be oriented so that the viewer will immediately look in the right direction after the cut — which is possible but always done. Invariably, there is no control over any cut's visual fluidity because every cut is a potential kind of a jump cut. However, without a frame, which in this case too acts as a frame of reference, a (jump) cut is not only an abrupt change of images but an instant change of the entire world, which is likely to be unpleasant and disorienting.

The disorientation forces you to find a new balance. For a moment, you lose concentration, and your attention wants instinctively to understand the new environment, which means looking around the place to feel safe. Only then can one catch up with the unfolding events.

The viewer is not being entertained or charmed by the experience but forced to stay perpetually alert and invest physical effort to keep up. Throwing the viewer in a new world, again and again, is nothing but exhausting the viewer.

Director Steven Soderbergh commented on editing in VR during a talk on interactive storytelling: "The ability to shoot a reverse and look into the eyes of the protagonist who is experiencing the story is the bedrock of visual narrative, and you just can't sustain something for more than 10 or 15 minutes in which you do not have a reverse in which you are looking at the character who is experiencing it. This is the difference between a game and a story." [51] Additionally, if the 360° camera was placed between the actors and the viewer could decide when to look at the other actor (do a reverse angle), a fast dialogue scene would soon become an exhausting physical exercise, rather than storytelling, let alone entertainment.

### 6.2.4. Aesthetic Poverty

The frame is a tool, not only the physical boundary of an image. If it were not true, cinematographers would not put effort into choosing its right aspect ratio. Linear composition, the purposeful arrangement of elements within the frame would be unimportant too. Framing and composition is a conscious choice made by all visual artists to express ideas and make an emotional impact on the audience. The frame plays a vital role in understanding the meaning of an image and conveying its emotion and aesthetic value. Furthermore, it gives visual context to every element within it.

Removing the frame altogether is not an extended effect of making the frame physically larger as in immersive cinema formats like IMAX. Eliminating the frame makes it harder to understand the images' context and appreciate the aesthetic potential they hold. The common viewer unskilled in the craft of cinematography practically becomes the camera forced to pass images to oneself without knowing the authors' intention. Such frameless images suffer from aesthetic poverty when compared to their purposefully composed counterparts.

To Morton Heilig, not having the frame is a matter of directing: "Since the conventional movie screen fills only 5% of the spectator's field of vision, it automatically represents his point of visual attention and the director needs only to point his camera to control the point of attention. But with the invention of means to fill 100% of the spectator's field of vision with sharp imagery, he must solve the problem of visual attention another way or lose his main aesthetic power." [20]

### 6.2.5. Lighting

A practical issue of 360° video is lighting. There is nowhere to hide anything, including lights from the all-revealing 360° screen. All light sources must be practicals, which is not always efficient. Cinematographers know that practicals must often be extended by other light sources that actually create the expected effect. A workaround would be to shoot each take twice as Eve Cohen did on Ashe '68. However, that denies the very idea of 360° video, because nothing could cross the hemisphere line. Without motion control, no shot could be in motion either, though camera movement is not always desirable, as discussed earlier. Moreover, even with motion control, actors would still not be able to cross the stitch lines. In effect, this would only permit shooting a very wide-angle shot.

Hard light sources tend to flare, and flares are not desirable on stitch lines, because they could reveal the stitch. Additionally, a hard source can cast a shadow of the camera itself. A sight not uncommon in 360° videos, which spoils the show and the immersion.

Thus the cinematographer is left with soft light only — emptying the toolbox used in filmmaking even further and limiting the means of expression to the technically feasible solution only. Digital postproduction could do service and make the hard camera shadow disappear. However, applying a powerful tool to fix an elementary issue does not make the use of hard light any more straightforward or reassuring.

### 6.2.6. It Is Not Film

Analysing the possible use of a cinematic toolset in 360° videos leads to the conclusion that 360° VR is not film. There is no difference if the imagery is a live-action capture or animation. Therefore the term VR film is not appropriate either. More appropriate terms would be VR attraction or, the already widely used, VR experience. The latter would do justice to Lanier's twelfth definition of VR: "VR is the technology of noticing experience itself." [4]

360° VR experiences need proper directing and attention guidance. Without it, they can quickly become a pointless looking-around self-indulgence the in technology.

The emotional impact of 360° VR is overrated too. The viewpoint often belongs to a third person and not necessarily the protagonist. That is in sharp contradiction to how VR experiences are widely presented (and marketed). Besides, the viewer becomes a bodiless presence in such an experience anyway.

Director Steven Soderbergh thinks, "It's going work in 10- to 15-minute bursts as an immersion into something, but it is never going work in a long-form narrative space. There are too many things that you're giving up that are crucial to a viewer's locking in to a narrative." [51]

The problem (of a non-existent frame) cannot be solved by thinking differently about the frame — e.g. that it is a sphere. The frame is simply not there. The misconception lies in assuming that 360° VR would be governed by rules similar to other visual media, film foremost. Therefore the only reasonable solution is to drop the idea of visual narration in spherical videos. However, this does not deny the capacity of 360° VR experiences to create an impression, or convey an experience or simple idea.

## 6.3. VR Installations

With all the above-discussed limitations of 360° VR, there is a small gap where it can and does work well. 360° VR can be beneficial as a supplementary programme to an exhibition, or similar event. If the potential VR audience has a backstory to hold on to, a VR experience established on this common knowledge can intensify the overall impression.

### 6.3.1. Space Descent

One such VR experience is the Space Descent 360° with Tim Peake installation [52] at the Science Museum in London. The installation offers a first-person audiovisual experience of returning to Earth from the ISS aboard the Soyuz TMA-19M descent module.

The roughly 3.5 hour trip aboard the capsule designed for a maximum of three crew members is condensed into a few minutes of a stereoscopic CGI 360° VR experience. The viewer is tightly strapped in one of the crew seats in VR. In the physical world, the viewer is seated in a comfortable armchair. Former ISS astronaut Tim Peake narrates the whole journey to Earth.

360° VR does not respond to any side-movements of the head(set). One can only look around. That also is what an astronaut can do in the extremely confined space of the return capsule. The limitation of the technology, in this case, supports the feeling of confinement. The illusion would be even more intense if the viewer would be strapped to a physical seat inside a sphere floating on water (or in a flight-simulator-like capsule) — imitating microgravity and thoroughly confusing the senses. Nevertheless, that would probably cause a few panic attacks of visitors more susceptible to motion sickness.

The narration takes care of guiding one's attention. The viewer knows where to look and what to see there. The movement of the capsule through space can be seen only through a few small circular windows. This minimises the probability of motion sickness, as one has the capsule as a frame of reference. Furthermore, the viewer here is not a third person but an astronaut in a spacesuit and can see oneself as such. Seeing oneself (or at least some kind of physical representation) is far more convincing than being an invisible observer.

### 6.3.1. The Ochre Atelier

"VR experiences had been created by museums and galleries before but Modigliani VR was to be a first — a VR experience that is fully integrated into a wider exhibition, and not simply a standalone add-on." [53]

The Tate modern created a VR experience[50] to paint a more vivid picture of the artist and his life. The gallery-goer is transported into Modigliani's modest Parisian studio with large windows lining the whole room. The virtual environment is a stereoscopic 3D rendering attempting photorealism. Looking at particular objects triggers the narrator to reveal further information, guiding the viewers gaze in desired directions.

The point of view changes a few times through slow fades to black. This approach minimises the possibility of motion sickness while still offering some change in perspective and exploration of the modest dwelling. Nevertheless, it can only work within a short time-frame without becoming monotonous. Looking around is the only true freedom of movement one has here.

The gallery had to make the VR experience accessible as widely as possible, considering the visitor composition. Therefore the conservative approach closely similar to a real commented tour of such a space. Seeing how the artist lived and worked gives one perspective on the paintings — how beauty can arise in the simplest and most modest places. The virtual visit of Modigliani's atelier is thought-provoking and makes the visitor equally appreciate the paintings and the artist. Undoubtedly, the VR experience serves its purpose well, leaving a lasting impression.

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[50] Viewable on Vive headsets and downloadable for a small price at https://www.viveport.com/64a94f1a-09eb-41b3-b251-d8de2b73b339

Nevertheless, Modigliani VR fails to do justice to the finer aesthetic qualities of the master's work. Though it is based on photographs and real word textures, the virtual environment is very rudimentary as far as lighting and colour rendition is concerned. The overall atmosphere and contrast are like in a computer game. A closer look reveals illogical lighting with unrealistic intensities. The colours are often oversaturated and unnatural, far from the lively but cultured colours in Modigliani's paintings. Surfaces look smooth, lacking the small imperfections that breathe in life to reality.

The technical immaturity of VR is partially the cause of such shortcomings. Furthermore, the aesthetics of VR and lighting, in particular, would greatly benefit from input and cooperation with cinematographers.

## 6.4. Immersion Without Interaction

360° VR's most significant flaw is that it is not interactive. One cannot move freely around the virtual space or manipulate with virtual objects. CGI 360° experiences can have some semi-interactive elements, but 360° spherical videos surely cannot. Jaron Lanier put it bluntly: "It mystified me to see people enthralled by the present-day fad for non-interactive VR experiences like the ones where you just look around inside a spherical video. If you can't reach out and touch the virtual world and do something to it, you are a second-class citizen within it. Everything else there is connected into the fabric of whatever world it is, but you alone stand apart." [4]

## 6.5. Storytelling in VR

### 6.5.1. Non-Linear Structures

Looking a few years back, many enthusiasts and professionals believed that VR was a new storytelling medium. There was no shortage of claims like "The visual language of VR storytelling won't evolve slowly the way that of film did; it will do so at light speed." [41] Ironically, the opposite seems to be true. VR storytelling has not made any progress since Morton Heilig's Sensorama.

Another opinion suggested that VR could be a "passively interactive experience," [3] an expression in conflict with itself. If something is interactive, it requires action and therefore, cannot be passive.

"Unlike video games, which require users to actively navigate through a conflict or narrative, VR films can allow the viewer to relax and watch but still control the action. It opens up interesting new ways to tell a story — like dialogue that changes depending on which character you're looking at, or alternate scenes that you can only see if you move your virtual self into a different room." [3] The extents of relaxation in VR films had been refuted earlier. Moreover, a dialogue that would change in the suggested way implies a non-linear narrative structure with uncertain and countless outcomes.

Such structures are not new. Kinoautomat[51], the world's first interactive film [54], let the audience decide about the story. There were two possible options for how the story should continue at each story junction. Nevertheless, the two previous plotlines always met when the audience was asked to make the next decision. The interactivity was, in fact, an illusion, though an entertaining one. Black Mirror: Bandersnatch[52] released on Netflix, is a more contemporary interactive film. Thanks to the possibilities of streaming, the interactivity was more elaborate and easier to achieve. Here too, the viewer can decide between two paths how the story will further unfold. However, the storylines in Bandersnatch are not parallel, and they diverge. The total viewable footage of about 4.5 hours is divided into 250 segments. [55] "Given the mind-boggling number of possible choices, there are more than a trillion unique permutations of

[51] Directed by Radúz Činčera, DOP Jaromír Šofr, Czechoslovakia 1967.

[52] Directed by David Slade, DOP Aaron Morton and Jake Polonsky, United Kingdom 2018

Bandersnatch.” [56] However, the possibilities are still scripted and countable. The audience is not as much in control as it appears because they can choose only from two predetermined options and at predetermined points. There are no loose ends. The audience is still an onlooker, not a part of the story. Nevertheless, the illusion is highly entertaining and encourages one to re-watch trying out different storylines.

### 6.5.2. The Mirage of VR Storytelling

Firstly, many falsely assumed that VR would follow comparable rules of the existing visual media as a predominantly visual medium. As VR took baby steps, it seemed that today’s one-minute VR experiences are the one-minute films of the Lumière brothers. We now know how far from true this is. The length of VR experiences is not scalable. A report on VR in 2020 states that the average time of a PC VR session is 32 minutes. [57] Wearing a (still relatively heavy) headset for extended periods causes fatigue, which restricts long VR experiences. The consensus is that 15–20 minutes is the ideal experience length.

Secondly, we need to remind ourselves that the VR movement of the 2010s started among fans of computer games, with Palmer Luckey as the flag bearer. It was their firm belief that VR could revolutionise storytelling — however of computer or video games. That notion of loosely substituting storytelling with entertainment seemed to be adopted and repeated across the entertainment industry without much critical thought.

As a form of entertainment, however, games probably can have positive effects and display aesthetic qualities. Nevertheless, that still does not qualify them as stories. That would either be a very loose and calculated interpretation of the word story or a hijacking of its meaning altogether.

We tend to interpret the experiences we had into stories. It is a natural way for us to store and process memories. Stringing little moments and experiences together, so they make sense, and the whole has a purpose. However, this cognitive process alone does not turn a handful of subjectively experienced situations into a story. Not a story thoughtfully structured and fabulated by an author where the recipient cannot change its course, timing, elements our outcome. Nor does wishful thinking turn entertainment into storytelling.

Thirdly, marketing uses stories as an advertising tool and calls it storytelling — with one fundamental difference — the purpose of such storytelling is not to make sense of an unfolding of events, but profit. An era of exceptional abuse of the word started in the 2010s. Everything had a story — food [58], furniture [59], clothes [60], and VR was no exception. The words story and storytelling became buzzwords. Waving them was a way to get attention, which in turn diluted their meaning.

Some understood the pursuit for VR storytelling very clearly, like Ed Catmull, co-founder of Pixar: "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." [50] Catmull plainly pointed out the difference between a narrative form and games: "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. Linear narrative is an artfully directed telling of a story, where the lighting and the sound is all for a very clear purpose. You're not just wandering around in the world." [50]

Lanier strongly emphasises the difference between film and (fully interactive) VR: "Fight against impulses you internalised in film school. VR is not cinema. For just one example, the watcher becomes invisible in a movie, but not in VR. The navigable virtual world is less important than the body of the user. What does she see when she looks at her hand? In a mirror? If the answers are modular—not central to the story—then you aren't yet designing for VR." [4]

# 7. Computer Generated VR — True VR

Polish writer, philosopher and futurologist Stanisław Lem described what we today call virtual reality as phantomatics. He asked a fundamental question: „We are faced with the following problem: how do we create realities for the intelligent beings that exist in them, realities that are absolutely indistinguishable from the standard reality but that are subject to different laws?” [34]

It would be rational to assume that a compelling (immersive) VR experience should be fully interactive, stimulating all senses and allowing movement without any restrictions. Only then could we speak of experiencing a world that would be impossible or hard to distinguish from reality. However, such an approach would quickly run into the limitations of technology. The technically possible would be far from the desired perfection.

Despite VR being far from a simulation of reality, people find it immersive and convincing enough to be entertained, or emotionally touched. Perhaps the average person is less sensitive to the differences between the virtual and real. Perhaps they are more tolerant of technical shortcomings, or perhaps sufficient suspension of disbelief is enough.

Jaron Lanier thinks, “VR is not about simulating reality, really, but about stimulating neural expectations.” [4] This thought gives rise to an entertaining paradox, that simply explains the state of VR at any given moment in time: People do not know what VR would be good for, but everyone would intuitively know how it should work. Therefore, let us examine how VR should work.

## 7.1. Visuals

### 7.1.1. Resolution, Latency and Field of View

Sight is our primary source of sensory information. Therefore, virtual reality is largely a stimulation of our visual system. Every other sensory stimulus can only improve the overall immersive experience, but sight is indispensable. Ever since VR headsets existed, they always sought to improve the visual perception by improving three technical parameters — resolution, latency, and field of view.

Higher resolutions provide more details and add realism to the digital image by suppressing its pixelated nature and supporting the neural expectation of what reality should look like. The goal is to have headsets with such high pixel density so that individual pixels would not be visible. So far, consumer headsets do not stand this test yet.

Low latency is essential to avoid motion sickness. A headset with low latency will meet the neural expectation of what the brain will see next when we move. "The primacy of latency was demonstrated dramatically in the early 1980s." [4] at a VR lab at NASA. The aim is zero latency.

Filling the entire visual field was already Morton Heilig's dream. Human field of vision spans roughly 210° horizontally and about 150° vertically, but not all of it is equal in quality. Just as only the retina's central region is sensitive to colour, peripheral vision contributes significantly less to stereopsis. [61] Not even today's professional industry grade headsets can cover the entire field of vision. Nevertheless, they come close enough to produce pleasing results. Consumer headsets cover a significantly lesser field of view of about 110°—120° which still delivers comfortable viewing. These numbers will likely increase to cover the entire visual field eventually. However, additional techniques like foveated rendering discussed later, will likely be involved to optimise performance.

### 7.1.2. Stereoscopic Quality

Good stereoscopy is a vital contributor to the overall visual experience of VR. As explained earlier, VR is ideal for orthostereoscopy. Orthostereoscopic projection faithfully replicates human vision showing things in true perspective and scale. Such images are physiologically natural to watch and do not cause extra eye strain or fatigue. However, orthostereoscopy seems to be poorly understood by VR developers. Firstly, the term is not used in the VR community. Neither is it mentioned in any of the establishing texts of VR like [20; 23; 24] nor in Jaron Lanier's [4]. Instead, the VR community uses synonymous terms — true perspective, true angle of view or true stereoscopy.

Orthostereoscopic VR is not a function of the headset or any other hardware, but a software setting that defines the interaxial distance and focal length of the rendered virtual camera pair. However, these parameters are often overlooked, resulting in a distorted perspective subconsciously corrupting the immersion.

Conversations with VR developers conducted during research for this thesis revealed that none had heard the term orthostereoscopy. Nor were they familiar with its synonyms used in VR. All required a lengthy explanation to grasp the concept. Many admitted having insufficient or no theoretical knowledge of stereoscopy, revealing that it was one of their last concerns in development. Stereoscopy was a matter of trial and error, without giving it much attention. Though these findings are not in any way conclusive, they offer some explanation to the possible cause of frequently seen poor stereoscopy in VR experiences. Surprisingly, stereoscopic quality in VR does not get the attention it got in films.

### 7.1.3. Eye-Movement Tracking

Eye-movement tracking (or eye-tracking) is a technology that measures movements of the eyeballs. It can measure the eye movements in general, determine the direction of one's gaze (gaze direction detection), and measure pupillary dilatation. Eye-tracking is commonly used as a research tool in psychology and marketing, as it reveals important information about visual perception and behaviour generally. The necessary equipment is small enough today to fit into a VR headset.

In principle, eye-tracking in VR is done by illuminating the eyes with infra-red light and then analysing its reflection. If the IR beam hits the pupil, it will be absorbed, if the beam hits the iris or sclera, it will reflect. One IR sensitive camera for each eye then captures the reflected light and creates an image pair. The cameras are usually placed off the eyes' optical axes to avoid the IR light reflecting directly from the retinae. The pupils' locations can subsequently be determined by analysing these images, which reveals where the eyes are looking. Such information can be used to optimise rendering for VR, leading to higher image quality.

The simplest application is automatic adaptation to interocular distance[53] (not to be confused with interaxial distance). VR headsets have the distance of their screens generally fixed, while some permit manual adjustment of the separation. Automatic IPD adjustment ensures the eyes look at the screens through the centres of the focusable eyepieces — Fresnel lenses[54] attached to the screens. This guarantees the best optical quality and viewing comfort. Automatic IPD adjustment is already used in some high-end VR headsets.

Another use of eye-tracking is foveated rendering. The fovea is a spot located roughly in the centre of the retina. It has the highest density of cone cells and is responsible for colour vision. It also is the area with the sharpest vision.

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[53] Called interpupillary distance (IPD) in the VR community.

[54] Fresnel lenses are used to suppress the so-called screen-door effect — seeing the image's pixel structure as if one was looking through a very fine mesh. However, Fresnel lenses are optically flawed and not particularly suitable as an element in any image-forming lens. Their use is likely to recede with growing pixel densities of screens.

Foveated rendering is an exploit of this physiological trait. Since only a small spot at the centre of our vision is in focus, it would be sufficient to do full-quality and high-resolution rendering only for the foveal vision. The critical areas of interest would be rendered with more visual detail, and the peripheral areas more coarsely without undermining the overall image perception. This method would significantly cut down on the necessary computing power and reduce the rendering time.

As screen resolutions will increase, foveated rendering will channel the processing power of any existing processors more efficiently. The implications are twofold. Firstly, VR headsets could cut the cord and do all the processing autonomously, without a computer, giving the wearer complete freedom of movement. Secondly, lower render loads mean lower power demands and lower heat generated by the hardware. Lower heat opens the way to slimmer headset designs, making them lighter and more comfortable.

One of the challenges of foveated rendering is accurately predicting the gaze point after blinking because "visual perception is a complex stochastic process." [62] A newly developed mathematical model claims to tackle the problem by studying fast saccadic movements of the eyes. The researchers could subsequently develop a model that reduced the inaccuracy of such predictions by a factor of 10. [62]

Viewing a stereoscopic image requires the skill to decouple convergence and accommodation. Though it is not unhealthy, it is physiologically unnatural, and over time, it can cause eye strain. This is why Charles Wheatstone insisted on having the lenses converge on the photographed object. In other words, have the object on the screen plane, where the stereo pair's parallax is zero — where convergence and accommodation are in agreement. Sharing this view, James

Cameron often adjusted the convergence during the take (convergence pulls) in Avatar to always keep the main object on the screen plane.

Eye-tracking could also be used to solve the convergence-accommodation conflict. In a virtual environment, we always have the advantage of knowing the exact positions of any object. The same applies to the viewer's position. Using eye tracking data, we can create a virtual line of sight for each eye. Eye-tracking is a complex process and requires a tremendous amount of precision. However, even without extreme precision, we can determine where the lines of sight cross by assuming that they will intersect on a virtual object's front-facing surface. This process reveals the convergence point. The distance from the eyes to the convergence point is the focal distance.

Nevertheless, the focal distance will always remain constant in VR as the eyes are always focused on the screens. As for now, headsets use simple fix focal lenses to create virtual images of the screens at a more pleasant (but constant) distance to the eyes. Changing this distance using varifocal lenses would force the eye to change accommodation. Additionally, there would have to be a slight depth of field effect.

Such a process is technically extremely complex but would mimic the natural way we see and cancel the convergence-accommodation conflict. Oculus has been looking into varifocal lenses for some time [63; 64] and has a prototype headset with a varifocal module [65]. Facebook, the owner of Oculus, is developing an artificial intelligence (AI)[55] based rendering system called DeepFovea [66] as a part of their research on eye tracking in VR.

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[55] Artificial intelligence is an area of research that tries to simulate various human capabilities.

Eye tracking has many more uses naturally. It could be used as an input device. Just looking at a virtual object would enable the user to interact with it. This would be much faster than pointing at something with today's controllers.

### 7.1.4. Colour Accuracy

A common problem with VR headsets is poor colour and contrast rendering. What developers see on their computer screens is not what they see in the headsets. Additionally, every headset model is different. Therefore there is a lack of image quality control across devices. Unlike in film and television, where it is clear what the screen brightness, display gamma, colour space and white points are, these aspects are not yet fully reflected in VR headsets — in consumer-level ones and professional models for industry use alike. Furthermore, image contrast is lowered by Fresnel lenses used in headsets, adding more complexity to the issue.

For example, the technical specifications of the Varjo XR-3 and Varjo VR-3 professional headsets state "Colours: 99% sRGB, 93% DCI-P3," [67] suggesting the displays are proprietary and do not even cover the sRGB colourspace which is being slowly abandoned on regular computer screens and replaced by the far more superior DCI-P3 colour space. Display gamma is not mentioned either.

Another professional-grade headset, the Czech-American XTAL does not disclose display gamma or colour space of its displays. [68]

The Oculus consumer headset line uses a different display gamma and colour space for each model. [69] Nevertheless, colour management is implemented to ensure colour consistency across models. [70]

Although VR has existed for some time, it is very young as an industry. Most of the development occurs behind closed doors of competing companies with little motivation to share knowledge or know-how. As a result, there is no cross-platform compatibility. VR is still largely in the early and wild stages of development without industry standards and best practices. However, "steps are being taken with several interrelated industry groups including Khronos Group, Virtual Reality Industry Forum (VRIF), DVB, MPEG and IEEE working independently to develop standards." [71]

### 7.1.5. Lighting

Light plays a vital role in any kind of visual media. After all, it is light that makes it possible to see. Cinematographers speak of three functions of light: a technical pre-requisite to create a photographic image, a facilitator of an object's physical properties, and a tool of artistic expression to convey emotion. These three concepts guide complex decisions on lighting. Although we have previously analysed and concluded that VR could not be approached like film, it is a visual medium. Therefore light in the virtual environment deserves to be treated with the same care as in the physical world.

One might think that virtual light sources are ideal for working with because they do not suffer from imperfections of their real counterparts. Virtual lights have no limits in where or how they can be installed, no cables, no stands, no electricity requirements, but unlimited possibilities of intensity, colour, uniformity, control, and overall quality. Unfortunately, it is not that simple.

Virtual lighting is quite different to film lighting — aesthetically as well as technically. The most notable aesthetic difference (and constraint) is that lighting for VR must work from every possible angle the viewer might look. Lighting a VR scene is similar to lighting a long take, where the camera will point in every possible direction.

Cinematographers typically try to avoid front lighting, as it makes images look flat. However, front lighting is much more forgiving in a stereoscopic VR experience than on a cinema screen. The flatness is not as disturbing because the viewer is immersed in a world, not looking at a flat 2D image without depth cues. The stereoscopy and free movement within the virtual world aid the depth perception.

The second difference concerns lighting faces. Faces are meticulously lit in films because they convey emotion and are crucial for cinematic storytelling. The level of care given to it is possible because of the highly controlled nature of close-ups. However, VR is not a medium of close-ups. Though recent developments in photo-realistic avatars [72; 73] make CGI characters with realistic human faces possible, lighting human-like faces in VR would not be rewarded by an emotional impact as strong as in films. Therefore VR lighting is more like lighting only the space of a set, not the actors.

Additionally, there is a technical limitation to lighting whatever action (moving objects in general). Realistic interaction of moving objects with light is computationally extremely demanding. With compromises, it is possible to create realistic but static lighting of a virtual environment. However, objects moving within the environment will not interact with the lighting. Realtime lighting effects can be used only rarely as they require extensive processing power. Foveated rendering gives hope this could soon change.

In the physical world, the laws of physics govern light and its effect on objects. Therefore we think of light in a certain way and work with it having these laws in mind. We take for granted that point sources follow the inverse square law, or that larger luminous surfaces emit softer light. Every single ray of a virtual light source must be calculated — how far it can travel, how many times it will bounce off a surface before it ceases to exist, how many rays a light source has — the physics of virtual lights is not the same. Moreover, virtual lights do not necessarily follow real-world physics, depending on the complexity of the software's lighting model (and if it has no errors creating unexpected lighting glitches).

Precise lighting for film and TV is possible thanks to a well-developed industry and technical means. Cinematographers can light with a high degree of confidence, knowing that the outcome would meet their intentions. However, the lack of standards in VR discussed earlier makes this much harder. Even the most elementary attributes like contrast or colour rendition become a matter of trial and error.

There are so many variables in the equation that photorealistic lighting in VR is not yet possible. Not with the current processing power of computers. The question is if the possible is enough to stimulate neural expectations. Certainly, it is not enough to simulate reality. Current lighting possibilities resemble the aesthetics of interactive 3D computer games. However, expectations of realism exceeding such entertainment would not yet be met.

## 7.2. Audio

In a virtual environment that stimulates visual perception to believe a world surrounds the viewer, sounds must be heard from all around as well. Spatial audio is commonly used in film and television employing several speakers distributed in a room. Nevertheless, VR headsets have only stereophonic headphones to recreate a convincing perception of spatial sound.

Binaural audio recording is a technique that recreates the way we hear sounds. Listening to such a recording through headphones creates the illusion of sound coming from a specific direction. In VR, the direction of the sound source must, however, adapt to the position and orientation of the viewer. This is called dynamic binaural sound.

The BBC has researched binaural audio for VR and demonstrated dynamic binaural sound in a VR experience called The Turning Forest[56], which premiered at the Tribeca film festival in 2016. [74]

Naturally, there is more research happening in binaural audio. Facebook, as a part of its massive long-term investments into VR, is looking into in too. [75]

Sound will surely play an important part in many VR applications, probably most in entertainment. Facebook's research on audio- and gaze-driven avatars [73] suggests that audio will become an important VR input.

## 7.3. Haptics

Ever since the VPL DataGlove, haptics has been a part of computer generated VR. The medium would not be interactive if one could not reach out and manipulate a virtual object in the most natural way — with bare hands.

Over the years, several approaches to adding haptic feedback have emerged. The oldest being the DataGlove which gave resistance when the wearer held a virtual object. Today, the possibilities are broader.

### 7.3.1. Gloves

Gloves are the traditional haptic feedback device in VR. There are several commercially available gloves with similar functions as the original DataGlove. All make it possible to feel and manipulate virtual objects. The VRgluv [76], HaptX Gloves [77] or Teslasuit Glove [78] are examples of exoskeleton gloves with haptic and tactile feedback enabling the wearer to feel textures. Gloves also have potential in various training simulations where the haptic feedback helps develop muscle memory.

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[56] https://www.bbc.co.uk/taster/pilots/turning-forest

### 7.3.2. Hand Tracking and Tactile Feedback

The UK and US-based company Ultraleap takes a much more intuitive approach in literally bringing hands into VR. The Leap Motion Controller [79] is a hand-motion tracker — a small and light-weight device attachable to any VR headset. The device scans and transposes the user's hand movements onto a pair of virtual hands. To do so, the Leap utilises two miniature near-IR cameras in a stereoscopic pair. The latency is remarkably low, and the precision high enough to detect gestures and finger movements. Anyone in a VR experience thus can manipulate a virtual object with bare hands. The downside is, of course, that there is no haptic feedback. Touching or holding a virtual object has no physical feedback effect on the skin and feels like performing pantomime.

The Prague based VR game development studio DIVR Labs uses Leap Motion Controllers on their on-site VR experiences like Golem [80], or Meet the Dinosaurs [81]. The VR experiences are set in an approximately 250 $m^2$ physical maze through which one can walk through and interact with certain elements like buttons, bars and wheels, that have virtual counterparts. Therefore, when one presses a stone in a wall to open a secret door, one sees a virtual hand pressing a virtual stone and simultaneously feels a physical interaction. The spatial alignment accuracy of the virtual to the physical objects is not entirely flawless, though. There also is a slight time delay. These glitches are not completely avoidable due to the complexity of tracking the headset's motion in the maze. Nevertheless, combining hand-motion tracking and interaction with physical objects is very intuitive, entertaining and enhances immersion making one forget the imperfections.

However, as various VR experiences share the same maze, the tactile sensations of the physical objects do not necessarily match the virtual objects' materials. The rough stone in the wall is smooth plywood in reality.

A group of researchers at Cornell University "have created a fibre-optic sensor that combines low-cost LEDs and dyes, resulting in a stretchable 'skin' that detects deformations such as pressure, bending and strain." [82] The research aims to make the technology commercially available for physical therapy and sports medicine, but as a byproduct, the sensor could give tactile feedback in VR, the researchers believe. This, in combination with hand motion tracking and real-world dummy objects, could be a much more natural alternative to bulky gloves. However, it would still require tracking the dummy objects and linking them in real-time to their virtual mirror-images.

### 7.3.3. Ultrasonic Feedback

Ultraleap is parallelly working on an entirely new strategy for haptic and tactile feedback. Ultrasound waves. Their Stratos pads are made of an array of miniature ultrasound speakers that can be activated individually and each at a different time. "The combined ultrasound waves have enough force to create a tiny dent in your skin." [83]

The company claims that the Stratos can create various tactile sensations in mid-air, pressure points, without the hand touching anything. The hand-motion tracking is handled by the Leap Motion sensor, which can work in tandem with the Stratos. The sensations that can be created are various click and dial feedbacks. The company claims their technology can also form lines and shapes to act as 3D controls in mid-air. However, there is no mention about the resolution of the pressure points so one may assume that the technology is still in the very early stages.

As a truly contactless technology, the ultrasound pads could have many other applications apart from VR. They could once fully replace touch screens at public places, making shared electronic device use safer and more hygienic. Perhaps when this technology advances, it could create room-sized force fields for VR strong enough to support a person on a virtual chair, as proposed by Ivan Sutherland. [24]

### 7.3.4. Full Body Suits and Virtual Skin

Haptic feedback, biometrics and almost full-body motion capture are what the Teslasuit offers. A full-body suit with 80 electrostimulation channels for tactile feedback and ten internal motion capture sensors, all packed in a two-part suite, that is "stretchable, breathable, durable and even washable." [84] The applications are wide-ranging from sports training, rehabilitation and various other VR training programmes, a shift of use compared to the VPL DataSuite designed for two users to interact in a virtual environment. It is only a matter of time, until such a haptic suit makes its way to VR entertainment, making all the VR enthusiasts wildest dreams come true.

A group of researchers across several universities in the US and Hong Kong are working on a device that will eventually deliver a much finer sensation. When applied to bare skin, the VR skin patch will let the wearer feel touch through an array of actuators. "The soft, wireless silicone device sticks to the skin and gives off vibrations." [85] So far the patch consists of 32 actuators, but the researchers plan to scale up. Besides VR, the applications span from simple touch transfer via the internet on video calls, to a wide range of medical uses.

The researchers believe the patch could eventually be deployed on a full-body scale. In combination with the Teslasuit, this technology could convey the finer sensations, and the bodysuit could take care of the coarser or more forceful sensations.

### 7.3.5. Other Haptic Feedback Possibilities

Not a single haptic feedback technology is universal. None can unite the comfort of bare hands, and the force feedback of bulky exoskeleton gloves. The developments suggest that diverse haptic feedback methods will be used depending on the VR applications they supplement. However, there are also low-tech possibilities of haptic feedback that can be creatively used in location-based VR entertainment.

The VR experiences of DIVR Labs use electric heaters and table fans to simulate the heat of a fireplace or a gentle breeze. A motion sensor turns both appliances on whenever the player is nearby. The sensations are surprisingly convincing and very unexpected when in-world. Move closer to the virtual fireplace, and the heat becomes more intense. Additionally, there is no delay in feeling the heat rise or fall. It feels real because it is real.

Companies that invested heavily in VR are studying hand tracking as a part of their broader VR research efforts. Facebook's Reality Labs is a team of researchers "developing all the technologies needed to enable breakthrough AR glasses and VR headsets, including optics and displays, computer vision, audio, graphics, brain-computer interface, haptic interaction, full body tracking, perception science, and true telepresence." [86]

Facebook is not hiding that all their VR research aims higher and is oriented at future products. This is in accord with CEO Mark Zuckerberg's comment at a federal courtroom hearing in January 2017, where he said, "I don't think that good virtual reality is fully there yet," and continued, "It's going to take five or 10 more years of development before we get to where we all want to go." [87] "Mr. Zuckerberg added that Facebook probably will have to invest more than $3 billion in the next decade to reach its goal of providing hundreds of millions of people with a good virtual reality experience." [87]

This gives some perspective on the scale of interest and investments happening in VR. It is important to understand that the VR we see today is probably only a set of research by-products, only small pieces of a larger picture that we might get to see in the next few years. VR development has a history of being fantastically optimistic about its future. However, never before has so much money been invested in VR as now.

A preliminary study on haptic feedback suggests that it affects emotional arousal during a human-virtual human interaction — a human interacting with an avatar driven by another human. [88] The researchers point out that the emotional impacts of haptic feedback in VR are still relatively unexplored.

## 7.4. Smell and Taste

### 7.4.1. Virtual Smell and Taste Research

“The sense of smell in many ways remains the least understood of the sensory modalities. For both animals and humans, it is one of the important means by which our environment communicates with us.” [89]

Olfaction and gustation are the least used senses in VR. We barely need these senses for spatial orientation like sight and sound even in the physical world. Unlike sight, sound or touch which operate in a limited spectrum (frequencies of electromagnetic radiation, air pressure and mechanical pressure respectively), smells are not limited to a fixed number of substances. [89] This makes them particularly difficult to reproduce by technical means like colour — sight can easily be deceived by mixing three primary colours to reproduce almost any visible colour.

Taste helps protect ourselves from potentially poisonous or unsuitable food. However, eating or substance detection is not a typical activity in VR. Besides, tasting something is almost always followed by eating it. Rarely do we taste just for the sake of tasting. Hence, culinary art is the most advance means of stimulating the gustatory system.

The thought of technically stimulating tase is not alien to VR but can be, so to say, far from tasty. Jaron Lanier joked about it on one of his talks in Kyoto, where VPL had VR showroom: „The actuator would be too disgusting to contemplate. It would be an icky mushy robotic protrusion you'd stick in your mouth. It would simulate the textures of different foods and release tasty chemicals while you chewed on it." [4] A year later he got a note from one of VPL's customers in Japan stating that they reading: „We are pleased to announce that we have recently achieved the ability to disgust you," [4] suggesting they created a VR taste device.

As repugnant and hilarious, this thought is, there is research happening on digital taste transfer. A group of researchers led by Professor Adrian David Cheok of Imagineering Institute Iskandar Puteri, Johor Malaysia and the University of London "propose an electrical tongue stimulation device, which the user places in their mouth to produce taste sensations. This technique operates by inducing weak electric signals by changing frequency and Pulse Width Modulation (PWM) produced by the circuitry." [89] The researchers claim that perception of all basic tastes (sweet, salty, sour, bitter, umami) can be created by electrical stimulation of the tongue. Test results on a group of volunteers are however not so convincing. Over half of the subjects "reported that electrical stimulation produces spicy, bitter, metallic, electric, and pressure sensations." [89] Nevertheless, the researchers remain optimistic and "expect this research to culminate with a wearable unit that could clip inside the mouth. Users could wear it in daily lifestyle situations for augmentation." [89] However, there is no mention of how it will impair the wearer's speech. Neither can this proposed device convey other perceptions connected to taste as the texture of food, the necessary biting force or crunchiness. Regardless of how unhealthy potato chips are, when they are not crunchy, they are not tasty.

The same researchers propose a digital smell interface too. It would electrically stimulate the sense of smell by having two silver electrodes inserted into the nasal cavities. However, the results are not satisfactory either. The tests "yielded different sensations and few odour perceptions," [89] and some subjects reported to have felt pain.

### 7.4.2. Practical Smell Stimulation

Vermont based OVR Technology created a chemical scent device that can be easily attached to the underside of most VR headsets — the ION. The device has nine scent actuators with interchangeable cartridges and can disperse scents in 0.1 ms bursts. Switching from one scent to the other can be done in 20 ms. The company offers a range of scents grouped in themes like camping, cooking, beach, spices, garden or even trauma. [90]

The intended range of application spans from therapy sessions in VR, military training (e.g. scents of diesel, garbage, and gunpowder), training firefighters to recognise various fires by the fumes, to VR entertainment like sitting around a campfire a scenting the burning wood. [91; 92]

The ION disperses the scents based on location triggers in the virtual environment. The triggers can be of various shapes and sizes depending on the nature of the scent. One would have to move closer to smell a bouquet or cup of coffee, while the campfire's smoke would be felt at a longer distance. The ION can create complex olfactory environments by releasing minimum amounts of a smell, quickly fading in time. Unlike dogs, we are not good at detecting the direction from where a smell comes from, "so concerns about 360° scent design aren't necessarily a point of friction," says the OVR Technology CEO, Aaron Wisniewski, former chef, mixologist and sommelier. [90]

The Spanish Olorama Technology [93] offers a different strategy to smells in VR. Their solution relies on small ventilators that can contain ten different cartridges with smells. The ventilators — Compact Generators — can be placed around in the room for location-based VR experiences. Location-based triggers would then have to activate the ventilator to release a smell.

Additionally, Olorama's technology is not limited to VR. A compact generator can be placed beside a TV set to enrich the TV watching to TV smelling. However, the company website offers no insight on how often one must ventilate a room not to smell burnt tires (a smell the company offers) for too long after watching a Formula 1 race.

Proponents of smell tend to be firmly convinced about its importance (and current lack) in VR. Electronic smell induction is not yet satisfactory, and chemical smell dispersion is not very practical. Either we need to attach another device to the headset, or we must deal with the mixing of smells and their accumulation over time in an enclosed space of location-based VR experiences. The immersion might be deeper, but the comfort of such an experience would be like having to climb a tree to see a monkey in a zoo.

Olfaction might be less understood and sidelined compared to sight and sound, though it undoubtedly plays a role in memory making, emotions, and deciding what to eat. Nevertheless, those instances are only small moments in time, fragments of our attention heavily depending on the situation and circumstances. It might be vital for a specific VR training simulation to have a particular smell always present, and in contrast, the same could be overstimulation in another VR experience. Not to forget the power of association, like evoking the sensation of heat by using warm colours. That technique could be good enough in most cases before there is a better technical solution.

## 7.5. Extended Reality

When Ivan Sutherland created his head-mounted display, it was, in fact, a mixed reality (MR) device. Jaron Lanier claims he came up with the term: "So far as I know, I also coined 'mixed reality,'" [4] but Magic Leap, a mixed reality company, trademarked it in early 2016. [71]

Augmented reality (AR), and mixed reality (MR), are both related to VR but have different use cases. Moreover, the terms augmented and mixed reality are sometimes used synonymously, adding confusion and confirming the need for standards in VR.

Extended reality (XR) is one such attempt to create "an umbrella term encapsulating Augmented Reality (AR), Virtual Reality (VR), mixed reality (MR), and everything in between". [71] The Khronos Group also uses the term XR in its OpenXR Specification to create a cross-platform standard. [94] Another term proposed to cover the full spectrum of AR, MR and VR technologies is synthetic reality (SR).

The unifying term is not as important as the observable trend of convergence of AR, VR and MR. There is a massive amount of research happening in all three segments, though it does not have as much media exposure like VR in the early 2010s. Moreover, not all of it is naturally yet public. The changing AR/MR/VR landscape hints toward a new mobile computing platform, that will smear the boundaries between the real and virtual world. The technologies will converge, but the spectrum of their possible use will grow.

### 7.5.1. Augmented and Mixed Reality

The line between AR and MR is thin. However, the consensus is that AR adds extra information as a layer to the existing physical world. Like driving instructions in the form of coloured lines on the road ahead, or lines and images connecting stars into constellations. AR already works quite well on smartphones and tablets, making it much more accessible than VR.

In contrast, MR adds virtual objects to the physical world. Such objects can look real and in principle, be manipulated — like furniture in a room (IKEA Place mobile application), plants in a garden or a dinosaur walking across the Charles Bridge.

Mixed reality too can run on a smartphone, tablet, or in a VR headset with front-facing cameras. In the latter case, the cameras should have the interaxial distance equal to the human interocular distance. Orthostereosocopic display is a must for convincing a mixed reality immersion.

MR has the advantage of realism because the baseline is the physical world. The catch is in the virtual objects. Currently, they still need to be relatively simple, like furniture or plants. Complex objects that move through space, like dinosaurs, are complicated to put into context with the physical world.

There had been problems with motion tracking, which resulted in the virtual objects not snapping perfectly to the physical world. It is relatively tolerable on a smartphone or tablet, but if virtual objects floated around in a headset or glasses, it would cause motion sickness. However, with the LiDAR[57] technology applied to depth evaluation, virtual objects stay perfectly aligned.

Occlusion of the virtual objects by real ones is not possible without perfect depth information. Additionally, virtual objects do not (and probably never will) physically interact with the real world.

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[57] LiDAR (sometimes LIDAR) is a combination of Light and Radar. It is a distance measuring technology that sends a laser beam (outside the visible spectrum) to an object and then measures its reflection with another sensor. Calculating the reflected laser beams’ return times and wavelength change creates a 3D model of the object.

The biggest stain on the overall realism is lighting. MR systems are not yet able to match the virtual lighting to real-world lighting. All virtual objects, therefore, look a bit out of place and fake. Perhaps this will be solved by involving AI that would analyse lighting and subsequently simulate it on virtual objects. The task is quite complex, but the recent advancements in AI are promising.

### 7.5.2. Google Glass

Perhaps the best known AR hardware that never lived up to expectations was the Google Glass. Introduced[58] in 2012, discontinued in 2015 and re-announced in 2017 as Google Glass Enterprise Edition. Glass, as it was called for short, ran into several difficulties. The most notable were privacy concerns — of the wearer and even more of everyone around. The built-in camera and microphone were too tempting to be abused. [95; 96] At one point, Glass wearers were given a vulgar name, not helping its broader adoption. A price tag of about $1500 did not help with a wide user adaptation either.

In contrast, Google Glass Enterprise Edition is a purely industry oriented device that only displays extra but relevant information to the wearer doing a particular task. The information is displayed on a miniature screen away from the direct line of sight.

### 7.5.3. Microsoft HoloLens

The HoloLens is an MR headset, oriented on manufacturing, education and healthcare. It uses see-through holographic lenses to display virtual objects as overlays onto real objects. These virtual objects can be manipulated with bare hands thanks to integrated hand tracking. Real-time eye-movement tracking provides proper depth rendering of the virtual subjects. The HoloLens also enables six degrees of freedom with positional tracking. [97] Although the

[58] https://youtu.be/4EvNxWhskf8

headset is more industry-oriented, entertainment will be soon coming to the HoloLens too. [98]

### 7.5.4. Magic Leap

After several years of development and secrecy, Magic Leap unveiled Magic Leap 1 — a wearable spatial computer. That is how the Floridian company describes its MR goggles. They are fully location-aware, support hand tracking and enable the user to manipulate virtual objects with bare hands or a tactile response controller. Applications range from the usual healthcare, education, and professional collaboration through virtual co-presence meetings. [99]

### 7.5.5. Apple ARKit

A shard of the ongoing research and development is Apple's ARKit. Although it is now closer to mixed reality, the company stays with the term AR. Probably for historical reasons, as the MR capabilities have been introduced along the way.

The ARKit is a software framework for developers to create AR and MR applications for what Apple calls "the biggest AR platforms in the world." [100] — their smartphones and tablets. The latest models of iPhones and iPads are additionally equipped with LiDAR scanners.

To date, Apple offers no AR/VR headsets or glasses, despite rumours that the company is working on some AR device, probably glasses. The company is typically tight-lipped about products to come. However, now and then, the CEO makes a positive statement about AR: "AR has the ability to amplify human performance instead of isolating humans. So I am a huge, huge believer in AR. We put a lot of energy on AR. We're moving very fast." [101] Numerous patents filed by Apple are suggesting an AR headset is in the works. The latest, titled Display system with localised optical adjustments was published on 17 December 2020. [102]

Cook is open about his preference of AR over VR: "I think it's something that doesn't isolate people. We can use it to enhance our discussion, not substitute it for human connection, which I've always deeply worried about in some of the other technologies." [103]

Using its existing hardware to fine-tune software for any future products seems like a pragmatic move for Apple. Furthermore, the research results' testing and validation are distributed into a global network of Apple product owners, perhaps hiding the bigger picture in plain sight. Once the rumoured AR device is rolled out, there will be plenty of existing software for it. This could solve the chicken and egg problem that crippled S3D and VR in its early stages.

Considering Apple's market orientation, it is clear that any AR/MR device, it would sell, would target the entertainment, education and professional sectors alike. Additionally, there would be a strong emphasis on privacy. If it had a pair of cameras (the original Google Glass had just one), there would be legitimate concerns over constant surveillance and recording, if hacked. Therefore LiDAR scanning is the likely physical sensing technology because it is already successfully used in Apple's existing portable devices.

## 7.6. Avatars

### 7.6.1. Ethymology and Origin

So far, we have looked into the perception of a virtual world. However, when there is a world, there must also be a conscious being perceiving it — a conscious being aware of its own physicality. In an interactive, computer-generated virtual reality, seeing oneself helps establish a sense of presence in the world. Such a bodily representation is an avatar.

The Sanskrit word avatāra means descent (especially of a deity from heaven), or the appearance of any deity upon earth. [104] However, VR (and computer games and pop-culture in general) use the word avatar as a virtual representation of a physical body. Ironically, turning the original meaning of the word the other way round.

Lanier claims that the word avatar in VR context was introduced by an American writer: „I distinctly remember the science fiction writer Neal Stephenson coining the term "avatar" — not as a word, obviously, since it has ancient origins in Hinduism, but as the term for your body in VR." [4] It happened in a 1992 novel titled Snow Crash: „The people are pieces of software called avatars. They are the audiovisual bodies that people use to communicate with each other in the Metaverse[59]." [105] Stephenson's involvement with virtual reality runs deeper being the "Chief Futurist of Magic Leap," [106] the aforementioned company. Avatars are thus rare conjunction of ancient culture, modern technology and science-fiction.

VPL had a VR tool called Reality Built for Two (RB2), which enabled a multi-person VR experience. This created the need to have a virtual representation of a person. The first avatars were "a smooth, cheerfully coloured figure with a cartoonlike head, an almost featureless body, and nimble but strangely tubular hands." [4] Ann Lasko, VPL's designer of DataSuits, had a more profound interest in avatars. Besides experimenting with non-human avatars, she designed the first avatar face in VR, "and she made it out of twenty polygons; an origami face." [4]

### 7.6.2. Self-Perception in VR

Avatars have been an object of interest and experimenting ever since they existed. VPL conducted a long "informal study of 'weird avatars that were still usable,'" [4] in the 1980s. [107] Lanier recalls him and his colleagues "took turns occupying a series of increasingly strange, but usable, nonhuman bodies." [4]

[59] The Metaverse is Stephenson's version of an advanced VR based internet.

The somewhat bizarre study ultimately led to a lobster avatar. Lobsters have five pairs of legs, the first pair equipped with large claws. Such morphology surely does not resemble human anatomy. Even with a DataSuit, it was impossible to meaningfully map two arms and two legs onto so many limbs. However, this was exactly the research point — how would people identify themselves with non-human avatars, and establish a presence in them.

The avatars were "controlled by mapping different degrees of freedom to the human user's body. Tracked movements that the user made in the physical world would be rendered as different movements of the avatar body. Thus, an eight-armed lobster could have each limb powered by the rotation of a wrist, the flex of an ankle, or some combination of the two." [108]

Previous research, such as the rubber hand illusion [109] (later conducted in VR too), and First Person Experience of Body Transfer in Virtual Reality [110] suggests that it is temporarily possible to create an illusion of body ownership transfer. In other words, the first-person perspective of seeing an avatar in VR can create a short-term illusion of physically being the avatar by owning its body. Homuncular Flexibility in Virtual Reality [108] researched how users would establish a presence in an avatar that would exhibit a feature like a third hand or limb movements that would not be a one to one match with the real body — like an enhanced or inhibited movement of a limb. All the mentioned experiments proved that users experience some level of embodiment.

VRwandlung[60] was a comparably strange VR experience installed shortly at the Goethe Institute in Prague in 2018. [111] The experience starts with the viewer waking up (seated) in bed as Gregor Samsa, transformed into an oversized insect. One could freely move around in space — Gregor's locked room in VR. Apart from the conventional head motion tracking within the small room, a pair

[60] A pun on Die Verwandlung, the German title of Franz Kafka's Metamorphosis.

of slippers and gloves with trackers helped with the hand and feet motion tracking. However, instead of hands, the viewer would see claws of the insect. Perfectly in sync to one's own hand movements and attached to an insect body visible in a mirror.

The VR experience had about a 5-minute time limit, in which the viewer was supposed to find a key and unlock the door. The sense of urgency was amplified by Gregor's father's voice shouting and banging on the door.

However, VRwandlung was not about learning to control an insect body. Metamorphosis is about a person feeling like an insect. Its adaptation as a VR experience was an effort to convey such feelings in a new medium. VRwandlung is a marvel of technology, a work of art and an early examination of an immersive medium. Nevertheless, the immersion cannot get across whatever interpretation of the original story, because the VR experience is conceived as an escape room — a game. The viewer's mind is preoccupied with fulfilling a task (finding a key) under pressure rather than contemplating the embodied character's personal feelings. Neither is the viewer motivated or challenged to explore controlling the non-human body. The claws are fully responsive to the hands, making it natural to manipulate objects in the room. The other limbs are not of much concern, since walking around the room in an upright position is effortless too.

The aforementioned experiments all concluded that a sense of body ownership is possible through an avatar's first-person view. However, those experiments were limited to physical reactions, like learning to control a limb or feeling a phantom pain, which can be explained by the brain's plasticity or homuncular flexibility. The brain learned a new skill, but the person was not closer to feeling like an insect.

VR tends to be overrated for its ability to (temporarily) transforming people into someone or something else, just because they see themselves in another person's body and experience some physical sensations. The illusion of body ownership is not enough to create a state of consciousness close to the embodied individual. Firstly, it is only an illusion of ownership, which appears to work as a survival mechanism. Like in the rubber hand experiment, when a person believes that their body part is in danger, they instinctively protect it. That is a threat response, not an act of compassion to protect the avatar. Therefore it is arguable that the viewer reacts on their behalf and that the sense of presence does not make the viewer feel as the impersonated avatar.

Consciousness arises upon awareness of sensory objects and mental formations. Regardless of how convincing the sensory input may be in VR, the mental formations will never be of the avatar, but always of the viewer. Avatars are mere virtual puppets we control. The illusion of temporarily inhabiting them with our minds does not bring our minds closer to understanding anybody they resemble. Therefore the consciousness that arises while embodying an avatar cannot be of the person or being it represents. It will always be the viewer's consciousness, despite feeling sympathy for the avatar. Invariably, that sympathy is the viewer's mental formation. It would be more accurate to understand presence as "the participants' conscious experience to feel to be in a different place from the one where they are physically located," [112] where the avatar plays no role again because the notion of a different place is revealed by a sensory perception unrelated to the avatar.

### 7.6.3. Impersonation in VR

Stanisław Lem contemplated the possibility of impersonating someone else through an avatar (without using any substitute word). In his thoughts, the viewer would not be an observer of another person's reality but would be actively engaging in that person's role like in a play. Lem thought of VR (phantomatics) as a "feedback art," that creates "bidirectional links between the 'artificial reality' and its recipient." [34] Nevertheless, his vision of VR was similar to Heilig's Cinema of the Future. In his opinion, "phantomatics offers a kind of experience whose 'privacy' can only be matched by a dream." [34] — a dream only for one person at a time.

Let us suppose the viewer would be in a VR experience of the Moon landing in Niel Armstrong's avatar, together with Buzz Aldrin's avatar (driven autonomously by software) and Michael Collins on the radio. It is unlikely that anyone immersing in such VR would have Armstrong's training and knowledge, let his personality. Even if the immersion was perfectly realistic, the viewer would not be under a fraction of the stress of the reenacted situation and would be aware that "neither the performed actions nor the persons appearing in the vision are material and hence real. The craving for authenticity would thus remain unsatisfied even by the most perfect vision." [34]

Lem concluded that, „the more the character one wishes to impersonate differs in personality traits and historical period from his own, the more fictitious, naïve, or even primitive his behaviour and the whole vision will be." [34] "This is why it will be very hard for phantomatics to develop into a mature dramatic form … drama needs personalities: characters in a play have them assigned in advance, while the phantomat's patron has his own personality and will not be able to perform the role outlined in the script because he is not a professional actor. This is why phantomatics can mainly be a form of entertainment." [34]

### 7.6.4. Self-Resembling Avatars

Origami faces and stick figures created a sense of social presence, but it is insufficient for the increasing visual realism of contemporary VR. Avatars are driven by motion tracking data of real people today. This makes the avatars move more like a human and in effect look more life-like, with all the quirks and imperfections but still essentially looking like a cartoon figure to the other person. What avatars have so far entirely lacked are credible facial expressions. A numb face with an empty gaze is not convincing of the presence of another human being, albeit in the virtual world.

Facebook Reality Labs is researching photorealistic avatars to aid social presence in VR — Codec Avatars. The company introduces the project as "creating new and better ways for people to connect, even when they're on opposite sides of the world." [72] The technology behind the research and the preliminary results give a glimpse into the (near) future of VR.

Codec Avatars are created by capturing an extremely high-resolution 3D scan of a person. To do that, Facebook built two studios, one for faces and one for full-body capture. The studios are in principle, a sphere with multiple inward-facing cameras.

The process starts with a 15-minute recording of various facial expressions and grimaces of the person whose avatar is supposed to be created. The captured data is subsequently fed into an AI system, which creates a photorealistic model, an avatar. Once a person with a Codec Avatar puts on a headset, their avatar will match their movements and facial expressions with almost perfect fidelity. Using audio and eye tracking data [73], the AI will even mirror such facial expressions that had never been recorded. The avatars are "almost indistinguishable from video," [72] when it comes to the facial geometry and texture. However, the weak link is lighting. The faces and bodies, respectively, are recorded with completely flat and soft lighting. This flatness stays with the avatars, making them look out of place and fake, just like virtual objects in MR. Once this is overcome, it could bridge the uncanny valley [113] of VR, which Lanier believes, "might make remote collaboration work better, and that might reduce humanity’s carbon footprint.” [4] However, what the other person is truly seeing is not an image of a person, but an AI-driven 3D model of a person. Therefore it would be valid to question the possibility of identity theft (like in deepfakes), or even life-like CGI faces created by merging existing faces of several people, creating fabricated identities.

Codec Avatars is not Facebook’s only avatar research project. “A different team at FRL[61] Sausalito is exploring physics-based avatars that can interact with any virtual environment.” [72]

The researchers explain “The point isn’t to replace physical connection but rather to give people new tools when they can’t interact in person, as telephone and video calls have.” [72] The research in VR, and avatars, in particular, hints at a new way of using VR — social VR — confirming Reality Labs’ declaration of interest in true telepresence.

## 7.7. Social VR

Social VR is a concept where VR acts as a communication or social media platform. A more advanced and interactive version of video calling intending to establish telepresence. The idea has been looming in works of fiction for some time — mostly in film and television.

Ready Player One[62] (originally a novel by Ernest Cline) depicts an alternative world, a social VR, called Oasis. Set in the year 2045 where the world is in economic, environmental and social turmoil, people seek refuge in the Oasis — using a VR headset and haptic feedback gloves. The film thematised VR and was “expected to raise the profile of the VR-based social platforms and be a

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61 Facebook Reality Labs

62 Directed by Steven Spielberg, DOP Janusz Kaminski, 2018.

catalyst for consumer adoption of VR." [71] The Matrix trilogy is a portrayal of a social VR too, though a very dystopian one.

The potential of social interaction in VR was tested by Neurons Inc., an applied neuroscience company, commissioned by Facebook. The study compared how participants would respond to a 20-minute conversation in VR and in person. The participants EEG and eye-motion tracking data had been recorded as part of the study. 93% of the respondents reported liking their virtual conversation partner, some claiming they would meet him or her again in VR or face-to-face. One surprising finding of the study was that introverts reported feeling more at ease during the social interaction in VR. [114]

Although the results speak in favour of VR, it has to be kept in mind that the sessions were only 20-minutes long, and the conversations progressed from small-talk to personal topics. However, the study does not specify the nature of these personal topics. Twenty minutes is roughly the period one can comfortably wear a VR headset without feeling fatigued. As a result, the study was conducted only under favourable conditions, not putting the participants under much stress, which can bias the conclusions in favour of social VR.

### 7.7.1. Social VR Worlds

As of February 2021, there are over a hundred social VR worlds [115], and naturally, the count is in a constant state of flux reflecting the evolving nature of the VR industry.

**AltspaceVR**, run and owned by Microsoft, is a cross-platform VR meeting space offering several worlds and even live events like concerts, stand-up comedy shows, or science talks. The emphasis is on entertainment and education. [116]

**Sansar** presents itself as a new live event destination, oriented at virtual concerts. [117] It was originally launched in 2017 by Linden Lab as a photorealistic VR successor to Second Life — their online virtual world introduced in 2003 [118]. Linden Lab sold Sansar in March 2020 [119] after CEO Ebbe Altberg admitted the company "leapt into the VR space 'a bit early' and had hoped 'for a bit steeper of a curve' in headset adoption." [120] The company is continuing work on Second Life, which is not designed for VR headsets (and neither has plans to support them anytime soon [120]) but has a stable user base of about one million. Jaron Lanier was one of the first people to be professionally involved in Second Life. [4]

**VRchat** is another cross-platform, game and entertainment-oriented social VR world. Users can create their own full-body avatars and other content. [121]

**vTime XR**, founded in 2015, claims to be "the first cross-reality social network." [122] The network emphasises spending "time with friends in AR, VR, or without a headset" [122] at many immersive virtual destinations.

Apple, which does not run any social network, bought Spaces, a "developer of location-based VR experiences that recently pivoted to launch a VR extension for videoconferencing platforms like Zoom and Skype." [123] The acquisition reaffirms Apple's increased interest in VR/AR.

Not surprisingly, Facebook has been heavily experimenting with social VR. It first released Facebook Spaces (no connection to the Spaces Apple acquired) in April 2017 [124] as an application to bridge physical distances between friends and family. As such, the accent was on social interaction. However, in October 2019, Facebook shut down Spaces to announce Facebook Horizon, a successor social VR platform. [125] Horizon is visually highly stylised and enables a wider range of activities from exploring virtual worlds, playing games and creating in the virtual world, with the social aspect in mind. As for February 2021, access to Horizon is still on an invite-only basis. [126]

Every social VR platform offers essentially the same — customised avatars, plenty of virtual places to meet, activities to do and a creative outlet that lets the users co-design the virtual worlds. The goal of social VR is to create a feeling of social presence or co-presence. However, with cartoonish avatars, co-presence becomes a metaphor. It will be up to the user to decide if they wish to be themselves or treat the social VR as a high-tech version of a role-playing game like Dungeons & Dragons. This would be acceptable and probably enjoyable as a form of entertainment, but not for fully-fledged social interaction that could convey subtle non-verbal signals. Moreover, a study [127] at the Department of Psychology of the University of British Columbia suggests that our assumptions about social presence in VR might be distorted.

A team of researchers conducted a study on social presence in VR by inducing contagious yawning. The study shows that yawning is triggered by a real person's physical presence, not by a simulated presence — an avatar. The experiments "revealed that the actual presence of a humanoid avatar within the participant's VR environment did not lead to a modulation of the contagious yawning response rates. This was true even when that person was directly facing the participants and displaying naturalistic movements, creating a more immersive experience within VR." [127] The study carefully concludes that their findings "suggest a major difference in the perception of social factors within and behind the scenes in VR, yet limitations to this study should be acknowledged." [127] One such limitation was the used avatar. Although it had realistic movements, it was not photorealistic. The researchers admit that altering it may lead to different results. Such findings generally validate the necessity for further research on social presence in VR. However, they also raise suspicions about the frequent claims of how VR will change the way we interact and how critically such claims have been examined before released and what true motivation lies behind them.

### 7.7.2. Towards an Alternate Social VR Reality

Social networks like to present themselves as a means of communication that connects people and bridges distances. However, their true purpose is to collect data on their alleged users (consumers, the masses) and monetise that data by selling it to advertisers (their real customers) as a service of targeted advertising. With surprising ease, social networks have managed to convince users to give up their personal data repeatedly, voluntarily and without being compensated. The only illusionary compensation is an impression that users are getting a communication tool for free. The collected data include the obvious — name, age, gender, education, employer, likes, interests, browsing history, geolocation, contacts, personal communication, photographs, but even how long one looks at an image. [128] These enormous data sets make it possible to aim an advertisement (in the broadest sense of the word) with unprecedented accuracy, because "Facebook can learn almost anything about you by using artificial intelligence to analyse your behaviour." [129]

On a relatively benign level, users can be persuaded to buy products advertised by the social network's customers. On a malignant level, when the advertisers decide to spread political or ideological messages, including propaganda and misinformation, social networks have the tools to skew any user's perception of reality in any direction. In other words, social networks manipulate people using data they voluntarily keep surrendering. The outcome is loss of privacy, mental clarity and living under surveillance.

"With old-fashioned advertising, you could measure whether a product did better after an ad was run, but now companies are measuring whether individuals changed their behaviours, and the feeds for each person are constantly tweaked to get individual behaviour to change. Your specific behaviour change has been turned into a product." [130]

Sean Parker, Facebook's founding president, offered first-hand insight into social media platforms' internal operation mechanisms. "The thought process that went into building these applications, Facebook being the first of them, ...was all about: 'How do we consume as much of your time and conscious attention as possible?'" [131] Keeping long-time attention on a social media feed is called engagement in social media circles. Parker continues, "That means that we need to sort of give you a little dopamine hit every once in a while, because someone liked or commented on a photo or a post or whatever. And that's going to get you to contribute more content, and that's going to get you ...more likes and comments. It's a social-validation feedback loop ...exactly the kind of thing that a hacker like myself would come up with, because you're exploiting a vulnerability in human psychology. The inventors, creators — it's me, it's Mark (Zuckerberg), it's Kevin Systrom on Instagram, it's all of these people — understood this consciously. And we did it anyway. …it literally changes your relationship with society, with each other." [131] Keeping a person engaged is, in fact, making them addicted.

Chamath Palihapitiya, former head of growth at Facebook confirms the company consciously manipulates users' behaviour: "We want to psychologically figure out how to manipulate you as fast as possible and then give you back that dopamine hit. We did that brilliantly at Facebook. Instagram has done it. WhatsApp has done it. You know, Snapchat has done it. Twitter has done it." [128] He also admitted to "feel tremendous guilt" about social media's potential effects in society. "The short-term, dopamine-driven feedback loops we've created are destroying how society works… No civil discourse, no cooperation; misinformation, mistruth." [132] Palihapitiya later downplayed his comments in a Facebook post saying they "were meant to start an important conversation, not to criticise one company," [133] However, he never revoked his critical thoughts.

When it is possible to manipulate someone's attention and behaviour by deeply understanding their inner desires, likes or political views, it is equally possible to make them believe in fabricated information or a false narrative, ultimately manipulating their entire perception of reality. "Control someone's reality and you control the person." [4] The damage done to the individual is ultimately devastating to society.

Not surprisingly, when Facebook announced that new Oculus headset users would have to log in through Facebook accounts [134], it sparked anger across the VR community and raised serious concerns about privacy and the future of VR. [135] The company has a long history of infringing privacy and data protection laws, including being sued by the FTC[63] in 2011 [136], and crossing paths with the GDPR. [137] In a recent case, it agreed to pay $550 million to the plaintiffs to settle a facial recognition lawsuit, "giving privacy groups a major victory that again raised questions about the social network's data-mining practices." [138]

Data-collection possibilities will steeply grow with the next generations of headsets. Eye-motion tracking will surely soon be a part of all VR headsets, as so many potential improvements of VR depend on it. To name one example — Facebook's photorealistic Codec Avatars. Eye-motion tracking will make it possible to gather previously unthinkable user data. 3D facial data will not only drive facial expressions of photorealistic avatars, but it could become a gauge of the wearers most intimate thoughts and feelings. Physiological reactions over which we do not have volitional control, such as pupil dilation, blush response and ultimately, any minuscule facial expressions that can give away our cognitive or emotional responses to stimuli. That is a treasure trove of data to understand and manipulate human behaviour, even if it would not be saved anywhere. After

[63] Federal Trade Commission

a few minutes in VR, “an advertiser could amass 400 times as much data as Cambridge Analytica ever had per user when it profiled Facebook users to devastating effect on behalf of clients seeking to influence the 2016 US presidential and other elections.” [135]

Social VR, just as any social media platform will strive to maximise user engagement, becoming a potentially even more dangerous data-hoarding and attention-seeking machine keeping the user in-world as long as possible, ultimately creating an even stronger addiction. This opens the potential of spawning entirely alternate realities much more suggestive and convincing than bare social media feeds of text, images and video. User data is the crops harvested for free that spins the mills of behaviour manipulation even faster. As long as users will not be honestly informed and compensated for the data they are giving out, there is no reason to believe that there will be a change of how their private data is used.

Unfortunately, the general discourse on social media is currently only confused with marginal issues like the legitimacy of banning public figures from the networks and restricting their freedom of speech on the internet. [139] Such discussions are only a reactive behaviour, which is not seeing the bigger picture — the flawed business model of social networks, excessive data collection, and the unregulated use of artificial intelligence which are the causes.

## 7.8. Artificial Intelligence

### 7.8.1. Convergence of VR and AI

“Artificial intelligence enables computers and machines to mimic the perception, learning, problem-solving, and decision-making capabilities of the human mind.” [140] AI is an umbrella term that covers every possible system simulating human intelligence. Subsets of AI are machine learning and subsequently deep learning.

From early on, Jaron Lanier envisioned VR to be separate from AI. A thought he formulated in his forty-sixth definition of VR: ”VR = −AI (VR is the inverse of AI).” [4] The definition is compact but sums the essence. VR uses existing data and visualises it in 3D. In contrast, AI is used to analyse large quantities of data or generate new data to eventually serve a different purpose — a clear distinction of how each technology handles data.

However, the convergence of VR and AI has already started. Aforementioned Codec Avatars by Facebook are one example. The territory is still relatively uncharted. Nevertheless, there is no reason to believe that it will stay so for long. The convergence of technologies is a natural step in their evolution. Today’s smartphones are the best example. They combine a telephone, diary, internet browser, E-mail client, a still and video camera, GPS navigation, an audio player and recorder, and the list could go on. Moreover, smartphones can serve as a VR device (Google Cardboard and similar contraptions). The intertwining of VR and AI will likely follow a similar path.

As a technology, AI depends on massive amounts of data, also called big data. Recent advancements in AI were made possible thanks to a swell of data in recent years — texts, images, audio and video — stored and shared over the internet. Big data is used to train an AI system to do tasks as object recognition. Feed an AI algorithm with a hundred thousand photographs with dogs in it, let it know that the pictures have dogs, and it will learn to recognise a dog in any other picture with some degree of accuracy. The more data the algorithm is fed, the higher the accuracy. More advanced algorithms (Deep Neural Networks) can be fed with more diverse data, and the algorithm will decide on its own what it shall identify, or learn. Similarly, AIs can also do pattern recognition in large data sets of, e.g. medical records to see early warning signs of a possible disease. AIs can also be used in a generative way, e.g. for translations. Feed the AI with enough equivalent texts in various languages, and the system will teach itself to translate any new text into whatever language it already is trained in. AI algorithms are present in our lives more than we might be aware of. They are used for spam filtering, sorting search results of internet search engines, speech recognition on smartphones, or YouTube or Netflix to suggest what to watch next based on our previous choices. AI is essentially what data it is given. A simple AI system was used to write this thesis, as well. Simple, because it only checked the grammar. An advanced AI would have written the whole text after suggesting the first few paragraphs and perhaps overall structure.

The theoretical pinnacle is an artificial superintelligence (ASI) — "a hypothetical agent that possesses intelligence far surpassing that of the brightest and most gifted human minds." [141] "An example of ASI might be HAL, the superhuman (and eventually rogue) computer assistant in 2001: A Space Odyssey." [140]

Kavya Pearlman, the founder of XRSI, a "not-for-profit organisation that promotes privacy, security, and ethics in the immersive environments," [142] claims "Research has shown that VR can record 20 million data points on a single user's behaviour and surroundings every 20 minutes." [135]

The potential use of such immense amounts of data could considerably change VR entertainment possibilities. Though storytelling would not be possible for reasons discussed earlier, VR experiences could become much more interactive and immersive if they had lifelike AI-driven avatars almost indistinguishable from humans, perhaps ready to pass a modified version of the Turing test.

Seeing Modigliani painting in his studio would be much more than just being in a room without his virtual presence. Interacting with his digital twin [143] in a simple conversation would be even stronger. Such AI avatars' reactions (and voices) would naturally be limited to the available data, which would be somewhat limited with historical figures like Modigliani. However, as a form of entertainment, a degree of stylisation would be understandable and acceptable. Moreover, such an AI character system would simulate a set of personality traits to breathe life into the avatar. A conversation with the avatar would be like the suspension of disbelief in a film when the audience accepts they are looking at a character in a story, not an actor playing a role.

A similar attempt, on a more modest scale, had already been made. Agence is, what its creators call, a dynamic film powered by AI [144] that premiered on the Venice International Film Festival in September 2020. [145] The VR form, which might be a fitter expression, falls somewhere between a game, interactive art and an animated film. The creators claim that it fuses three elements — their authorship, the audience's input, and the machine intelligence. The story is about five AI beings who have to cooperate not to fall off their planet. The viewer can upset this balance, causing the creatures to react. However, due to the AI, the creatures learn and adapt. In turn, every time the viewer watches, or more precisely interacts, with the form, the creatures react differently. It is questionable if the words story or storytelling would apply to the whole form, even though it starts with a narrative voice. As soon as it falls silent, the form moves closer to a game with some cinematic elements like cuts. However, those cuts are more ornamental than aiding storytelling. Agence, just as many other attempts at VR filmmaking limps in visual storytelling despite being visually poetic.

### 7.8.2. Data for AI Avatars

Facial expressions, eye movements and gaze direction data retrieved from headsets combined with AI will surely make photorealistic avatars look lifelike but at a high cost. Such data is inherently biometric, making them even more sensitive. The collectable volumes will be tempting to create stronger and more tailored emotional responses. The AI tentacles will wind even tighter around the users, gripping their attention firmer than the most charismatic human manipulator. The same data can potentially be abused to create social VR deepfakes, making current fake social media accounts (bots) look primitive. The implications are perhaps beyond our imagination.

However, AI itself is not the problem. Nor is the inevitable convergence of VR and AI. Any technology is not intrinsically good or bad. The intention of its use is what matters — or, the failure to not act when the technology's adverse effects are understood or suspected. Researchers at the Max Planck Institute for Human Development admit "there are already machines (machine learning algorithms)[64]. that perform certain important tasks independently without programmers fully understanding how they learned it." [146]

In fact, this black-box mechanism is a design implication of neural networks (a network of algorithmic calculations that attempts to mimic the perception and thought process of the human brain [140]). They contain one or more so-called hidden levels where the machine learning algorithms process the input data. However, the mechanism within the hidden layers remains concealed even to the creators of the system.

The late theoretical physicist Steven Hawking and technologist Elon Musk think a deeper discussion about AI should start before the technology could get out of hand. [147] Both expressed concerns over superintelligence, which [141] proved could neither be contained nor probably even detected by humans. Dial F for Frankenstein [148] by Arthur C. Clarke illustrates how a sudden takeover by a superintelligence could look like.

Although superintelligence is still a theoretical concept, recent advancements in AI should be a reminder to start a wider discourse on technology and its effects

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[64] Author's note.

on the human mind. Ethical standards need to be incorporated into the legal regulations of many current and emerging technologies before they inflict damage that would become too big to heal.

## 7.9. Virtual Reality and Inner States

### 7.9.1. Not an Empathy Machine

Soon after the revival of VR in the 2010s, the word empathy started to be mentioned more often alongside VR. Claims that virtual reality could convey empathy were spreading fast and soon became iconic for VR marketing. [149]

VR and empathy were mentioned together in March 2015 on a TED talk given by Chris Milk. [150] As an art school graduate and multimedia artist, he wanted to step out of the cinematic frame and try telling stories differently, which led him to experiments with VR.

Together with Gabo Arora, Milk shot an 8 minute S3D 360° VR short called Clouds over Sidra[65]. The story is narrated by Sidra, a 12-year old Syrian girl living in a refugee camp in Jordan. Milk claims that VR "connects humans to other humans in a profound way," [150] he has never seen before and that it can "change people's perception of each other." [150] "So, it's a machine, but through this machine, we become more compassionate, we become more empathetic, and we become more connected. And ultimately, we become more human." [150]. Though Milk was only giving a 10-minute talk, he offered no reasoning to these unsubstantiated claims he made about VR.

Clouds over Sidra, just like any other attempt at making a VR film, is not a film. Here too, the absence of closeups makes it hard to picture emotions of a person. A few overly high angles make it impossible to see the action, catapulting the audience out of the pseudo-narrative immersion by feeling awkwardly tall. The

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[65] https://youtu.be/mUosdCQsMkM

stereoscopy is exaggerated, making the viewing painful and not adding any value to the image. The overall pace of the connected shots is slow and undramatic. Again, it is almost entirely the constantly present audio commentary that does the storytelling, not the visuals and certainly not the immersive aspect of VR.

"I don't want you in the window, I want you through the window, I want you on the other side, in the world, inhabiting the world," the author explains. [150] Milk's main misconception of VR is thinking of it as a derivate of cinema and forgetting that inhabiting a world means the VR experience must be interactive — which Clouds over Sidra is not. The viewer is just a passive onlooker. "To enable this self-centred experience multiple modalities such as vision, audition, tactile and proprioception must persuade the brain that the realism is omnipresent" [151].

Milk's words about VR being the ultimate empathy machine became an advertising trope of the mid-2010s, but they also got frequently cited with critical comments: "It's confusing immersion for empathy" [152], "The VR industry is operating with a muddy, unclear, superficial definition of empathy, one that is forgiving to truisms like 'standing in another person's shoes.'" [153] Nevertheless, the word empathy struck and was often used when talking about the impact of VR [154; 155].

Claims that VR can convey empathy or other mental states are essentially flawed. Seeing refugees in VR might help understand the physical reality of a refugee camp. However, as a medium unable of storytelling, VR can hardly tap deeper into any human's emotional state more than a conventional film. The horror of fleeing home with a few belongings that fit in a backpack, without knowing if or when one will be able to come back, and if there will be a home to come back to at all is just a fraction of fears a refugee feels. Such anxieties are not conveyable by any technology. Not even if the VR experience faithfully reproduced all the environment's physical sensations, like sounds, heat, humidity or smell. Attributing the emotional response to Sidra's story to VR is overestimating its possibilities as a medium. "Nobody thinks that going downtown without your wallet will make you appreciate poverty — why should these simulations do any better?" [156], asks professor of psychology Paul Bloom. He points out another limitation of VR — safety and control. "During the debates over the interrogation practices of the United States during the Iraq war, some adventurous journalists and public figures asked to be waterboarded, to see what it was like. They typically reported that it was awful." [156] VR is the same because one always can take off the headset and leave the immersion, just like the journalists could say stop. Another factor to consider is time, "You can't take an event of minutes and hours and generalise to months and years." [156]

In [157] Bloom shows there was a surge in the use of the word empathy in the mid-2010s. "Right now, there are over fifteen hundred books on amazon.com with empathy in their title or subtitle," [157] including "marketing books ('How to use empathy to create products people love')." [157] Empathy has become a fashionable and agreeable word to use.

Lanier admits to had toyed with the word empathy earlier, though less categorically. "I might have been responsible for bringing the term 'empathy' into high-tech marketing, because I started talking about VR as a tool for empathy back in the 1980s." [4] This hope is reflected in Lanier's "Fifty-first VR Definition: The medium that can put you in someone else's shoes; hopefully a path to increased empathy." [4] However, he acknowledges that "VR, for all it can do, is not yet a medium of internal states." [4]

VR started using empathy rather customarily without understanding the implications of the word. A close and related term to empathy is compassion. Nevertheless, they are not synonyms. While empathy is the ability to feel with someone, compassion is the ability to feel for someone and actively help in an altruistic manner. The difference is psychological, as well as neurological, as documented in [158]. The paper shows that empathy is a broader concept which can lead to two possible states — compassion and empathic distress. The outcome of emotional distress is negative emotions towards oneself, including stress, or burnout. In contrast, compassion as a learnable social emotion leads to positive feelings, including motivation to help others without being emotionally burdened by their ordeal. [158]

The differences between the two mental states were further proven by fMRI (functional magnetic resonance imaging). When watching short videos of people suffering, the test group that underwent compassion training (using the mediative technique of loving-kindness) displayed activity in different brain regions compared to the untrained subjects. The result was repeated when the untrained group was given compassion training and subsequently scanned.

"Taken together, these results underline the important distinction between empathy and compassion, both on a psychological and neurological level. Accordingly, exposure to the distress and suffering of others can lead to two different emotional reactions." [158]

The construction of the experiment (showing people in distress) is very much like Clouds over Sidra. However, the emotional reaction to such stimuli depends on the viewers' mental training and overall emotional stability [158], not the technology. Assuming that VR could promote empathy illustrates the loose use of the word. Clearly, nobody would be a proponent of a device that would cause emotional distress, not to mention their damaging long-term effects.

Although VR will most likely never evoke internal states of mind directly, it can undoubtedly indirectly trigger a wide range of emotional and physiological responses. Some reactions can be traced back to motion sickness. However, the mechanisms of others are still to be explored and understood.

### 7.9.2. Memories and Other Long-Term Effects

As VR is more frequently used in various psychological studies, an experiment conducted at the Institute of Psychology at the University of Osnabrück examined the long-term effects of VR immersion. The results suggest VR impacts autobiographical memory. [159]

Two groups were shown a 28-minute long motorcycle ride through Osnabrück shot as a 360° video. Group one watched the video on a TV screen with their hands on a table. Group two were given VR headsets and were holding bicycle handles during the virtual ride. When asked about their moods immediately after the experiment, both groups answered similarly. The immersive experience seemed to have no direct impact on the mental states of the participants. However, 48 hours after watching the videos, both groups had been called back for another test. Both groups had been presented with 90 frames from the video and asked to answer if they remembered the particular scene or not. The VR group "rated their experience significantly more realistic as compared to the video-group," [159] and performed more than twice as well than the TV screen group. "Memory traces formed under the immersive sensation of a virtual experience are characterised by richer content and more elaborate associative networks." [159]

The paper points out that such "considerations lead to the question of the psychological harm of virtual experiences." [159] The conclusion does not imply that this could be generalised as harmfulness of computer games. Nevertheless, the researchers voiced concern that, "The (envisioned) immersion of VR applications might even more blur the border between the real world and computer games." [159] A blurred line between reality and a VR simulation would be a very positive outcome for education or entertainment. In contrast, a lowered ability to distinguish true from virtual could be a serious concern in the context of social VR. Additionally, the paper points out that, "Disturbing or traumatic VR experiences also might have adverse long-term effects." [159]

Long-term effects of VR are still vastly uncharted territory. So far, there is suspicion that heavy use of VR headsets could lead to myopia or difficulties with depth assessment due to the accommodation-convergence conflict. VR headsets also have screens in extreme proximity to the eyes. There are concerns about adverse effects of the heat generated by the screens on the eyes. Research on such topics is very likely to happen in the near future.

There also is a consensus that children should not be exposed to VR before the age of six. Some say even eight years — before they develop motor skills. [4] However, it is unlikely that there will be any research on the effects of VR on children given the ethical and practical implications. VR hardware manufacturers are cautious and advise that VR is not suitable for children under 12, or 13. The general concerns are that children cannot consciously realise eyestrain and thus would not feel the urge to remove the headset. Furthermore, there are uncertainties regarding the convergence-accommodation conflict and the potential negative impact on children's brain development. [160] Considering the conclusions of [159], it also remains unknown how much harm a traumatic VR experience could do to the developing brain.

## 7.10. Direct Brain-Computer Interfaces

### 7.10.1. Phantomats

Experiencing virtual reality through a direct connection of a device (a computer today) to the brain is not a novel idea. Stanisław Lem described such a device — a Phantomatic generator — and theorised how the human-machine link would work: „This man's brain will have to be connected to a machine that will send streams of olfactory, optical, sensory, or other stimuli into it," [34] and continued by suggesting how his phantomatic generator would operate: „The machine will have to send the impulses produced by his brain in response to the impulses it receives to its own subsystems, and it will have to do it instantly, in a split second." [34]

Lem was convinced that phantomats would not create perfect simulations, even though they would provide the brain with neural stimulation to spoof it into sensing muscle activity. In his view, a perfect simulation would require a phantomat to predict every possible outcome of the immersed (phantomatised) person's actions and decisions and contain data about everything — an impossible condition. His vision of full immersion is thus a more generic dream-like vision. However, Lem expected these general entities, environments and persons alike, to be adaptive and readily react to the dreamer's mind. Such a complex process would, however, require artificial intelligence (which Lem examined in [34] as intelectronics, though not in combination with phantomats) even to meet Lem's idea of a dreamlike-state. He concluded that this would ultimately be the flaw of phantomatics because the immersion would not be realistic enough. "The craving for authenticity would thus remain unsatisfied even by the most perfect vision." [34] Phantomatic simulations are only a single-person ride, a private dream-like state. No two people can share the same phantomatic experience, just like they cannot share a dream, making the experience a very lonely place where one cannot trust anyone else — simulations, inevitably.

Jaron Lanier admits to have been confronted with the idea of direct stimulation too: "Does that mean that VR ought to be accomplished by direct connection to the brain in the future? This is one of the most common questions I have been asked since the earliest days of VR." [4] However, he is not in favour of direct brain stimulation for VR and considers the question misleading, as direct brain stimulation would violate the natural mode of human perception. "The brain and the sense organs are an organic whole. In the embryo they teach each other what form to take, and in childhood they train each other." [4]

The Matrix films are a dystopian depiction of such a direct machine to brain (reality) simulation. A machine created by an artificial intelligence conceived by humans eventually controls and enslaves humans. Lem hypothesised a similar dystopian civilisation-scale concept — the Superphantomat — where humans would not share the experience but live it individually, in parallel dream-like states, "supported by automatic devices (e.g., those introducing supplements into their blood)." [34] Unlike the human-breading Matrix, a Superphantomat could only support human life for one generation, making it a form of collective suicide.

Setting aside the science-fiction genre's dramatisation and extrapolation, a computer-brain interface is not so far from (virtual) reality.

#### 7.10.2. The Link

Entrepreneur and technologist Elon Musk who is producing self-driving electric cars, launching reusable rockets to transport astronauts and cargo to the ISS, digging tunnels under cities to revolutionise transport and ultimately wanting humans to colonise Mars, is working on connecting the human brain to a computer. Musk ultimately wants a symbiosis of humans and AI. [161] His company Neuralink "is building a practical brain-machine interface[66] for a wide range of applications," [162] called the Link.

The Link is a device intended to be implanted into the brain, containing threads a thousand times thinner than a human hair. Each of these threads have several

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[66] Brain-machine interface (BMI), is sometimes called brain-computer interface (BCI).

electrodes that will be directly inserted into the brain by precise robotic neurosurgery. [163] Neuralink wants to create bi-directional communication so that electrical signals can be read from and written to the brain so, “a person with paralysis can control a computer mouse or keyboard. Or, information can be written back into the brain, for example to restore the sense of touch.” [163]

Neuralink performed a public demonstration[67] of its 1024 channel prototype implant in August 2020. They presented a pig with a read-only implant connected to its snout areas in the brain. Whenever the pig sniffed or touched something with its snout, the Link delivered real-time data of the electrical signals from the animals’s brain. The signals were visualised in a spectrum-analysis graph and converted into beeps providing a proof of concept. The demonstration also stressed the device’s safety by presenting a pig that used to have an implant which was later removed. The pig seemed perfectly normal.

The company claims the Link is a starting point and hopes to improve the device by tapping into more brain areas accessing “new kinds of neural information”. [164] They also claim that the Link has potential “eventually to expand how we interact with each other, with the world, and with ourselves.” [164] This can be closely reminiscent of the language used by social media companies. Therefore concerns about privacy and the ethics of collecting, processing and storing such intimately private data are more than appropriate.

It is important to keep in mind that the Link is not an end product to alleviate various medical conditions, but an interface that communicates with other electronic devices wirelessly. As such, it has many possibilities of use. In the Q&A session following the public demonstration of the Link prototype[68], Musk

[67] https://youtu.be/DVvmgjBL74w (see approx. 0:12:10)

[68] https://youtu.be/DVvmgjBL74w (see approx. 0:30:38)

admitted that the device could once be used for gaming. However, the answer was meant in the context of controlling a computer game by thoughts alone.

Once the Link reaches its goals, which will take a very long time, and achieve substantial read and write capabilities, such a device could be useful for VR, AR or generally XR. Sensory information could be software-generated and sent to the brain directly. Sensory perception would not be purely physical anymore but would become an electronically augmented sensory perception — a composite of physical reality and the virtual world.

However, such a process of cyborgisation is far from simple. "To begin with, there are significant risks of medical complications—including infections, electrode displacement, haemorrhage, and cognitive decline—when implanting electrodes in the brain." [165] While certain sensory stimulation would help the disabled, just as the Link intends, direct sensory stimulation of healthy individuals run into many practical, not to mention ethical, questions. "Most of the potential benefits that brain implants could provide in healthy subjects could be obtained at far less risk, expense, and inconvenience by using our regular motor and sensory organs to interact with computers located outside of our bodies. We do not need to plug a fibre optic cable into our brains in order to access the Internet." [165] Undergoing the risks of neurosurgery would have to outweigh the uncertain gains, which would have to be considerably more significant and meaningful than the currently displayed read-only possibilities with 1024 channels. Stimulating all senses would require inserting electrodes in multiple areas of the brain, making the procedure even riskier. Therefore, invasive direct brain-to-computer interfaces are likely to stay for patients with severe medical conditions or eccentrics who are happy to be first in anything.

### 7.10.3. Facebook BMI

Any technology intended for the masses must be easy to use, easy to buy and easy to maintain or replace. BMIs for the masses must be unceremonious as sunglasses.

Since 2017, Facebook Reality Labs has been working on a non-invasive brain-computer interface that would read words silently spoken in one's mind and convert them into text. [166] Part of the study was entrusted to a group of 60 researchers at UCFC[69]. The team used an electrocorticogram (ECoG) to record electrical signals from the brain's surface and then trained a neural network to translate these electrical sequences to sequences of words — similar to how neural networks translate from one language to another. This way, they were able to "encode each sentence-length sequence of neural activity into an abstract representation, and then to decode this representation, word by word, into an English sentence," [167] with an error rate of about 3%. Facebook claims this is a break-through in accuracy, compared to previous studies which had error rates higher than 60% even when tested on much smaller vocabularies.

Unlike electroencephalography (EEG), electrocorticography requires electrodes to be placed on the surface of the brain. Such a procedure was possible thanks to UCFC's efforts to help people who lost speech. However, Facebook is open about its intentions for this technology: "At Facebook Reality Labs, we're focused on exploring how non-invasive BCI can redefine the AR/VR experience," [166] indicating the research is only a lap in a longer race. This suggests that future VR/AR applications or experiences could be limitedly mind-controlled to execute certain commands.

While the idea of controlling a computer game (or moving through a virtual world) with the mind can be an entertaining thought, the practicality of

[69] University of California, San Francisco

controlling a computer, in general, is more complicated. Existing voice assistants in smartphones are a good parallel. One can give simple commands like "play rock music," or "call dad." However, they are useful only in certain situations, like driving. The conventional way of using one's hands to operate smartphones still feels much more natural in day-to-day use. Complex actions, like browsing the internet, which require significantly more concentration and input, would feel more irritating than entertaining with voice or mind commands. The technical possibility, though still not quite mature, is not always a guarantee of usefulness.

### 7.10.4. BMI for VR Gaming

OpenBMI offers open-source BMI hardware and software for VR and AR headsets — Galea. The company claims Galea is the first device to integrate EEG, EMG (electromyography), EDA (electrodermal activity), PPG (photoplethysmography), and eye-tracking in a single headset. This combination of biometric data is intended to give "researchers, developers, and creators a powerful new tool for understanding and augmenting the human mind and body." [168]

Valve's resident experimental psychologist Dr Mike Ambinder admits the game industry is eagerly waiting for such technology, as it could "leverage this data" [169] for game design that would react to the player's mental state — be it happiness, sadness, frustration or boredom. Ambinder further elaborates that the use of such datasets "could span everything from creating better tutorials by learning about the user's individual ability to learn, to making games capable of learning how players want to play as opposed to how they should play." [169]

The last-mentioned use case is ethically questionable for at least two reasons. Firstly there is the aspect of collecting and processing highly sensitive data, which is, under normal circumstances, gathered only for research purposes. Secondly, the statement skates on thin ice by implying that the intention is to exploit the unconscious and involuntary aspects of human behaviour in a feedback loop that adjusts a computer game and makes it more desirable. Ultimately, that would change the gamer's reactions and behaviour into a machine-aided addiction. Being manipulated would become a routine aspect of entertainment, wrapped as a feature gamers want.

Nita Farahany, a professor of law and specialist in neuro-ethics, is concerned about the impacts of BMIs, especially if they are bi-directional. "We have no idea what the implications of making those alterations are long term, and how much behaviour can actually be manipulated. Can you stimulate craving or can you stimulate addiction? Could you stimulate particular preferences?" [170]

## 7.11. Full Immersion

The practical possibilities of stimulating the senses for a VR experience are so far only indirect — though stimulating our sensorimotor organs. Although much research is going on, BMIs are still in their infancy and probably very far from altogether replacing sensory stimulation. Neither are the existing indirect means advanced enough to outsmart the senses not to notice the very fabric of the illusion. Faithful illusions would have to be so persistent that the mind would not question their reality. And not just one mind, but many minds collectively experiencing and ultimately sharing such a virtual reality. However, the hardware and computing power necessary for such exceptional simulations is beyond current possibilities, equally as the simulation software.

Let us just shortly suppose that we would have the technical means for creating virtual worlds indistinguishable from reality. Likewise, we would have a contained advanced artificial intelligence connected to the software running the VR simulation. We would also have sufficient energy to run the powerful hardware persistently and the means to cool the heat generated by it — a serious engineering task itself. As Arthur C. Clarke suggested, "The only way of discovering the limits of the possible is to venture a little way past them into the impossible." Let us venture a little into the impossible, and consider it possible to step into a simulation of reality collectively with other humans and AI-driven avatars alike.

Such a reality simulation would have to follow natural laws, so it does not raise suspicion of being a simulation. All senses would be stimulated, just like in reality. The simulation would provide realistic feedback to the body, which could feel its own motion such as muscle-flexing — everything controlled by volition. Autonomous processes like breathing or heart-beat would naturally follow the body's needs based on its activity and therefore would not be part of the simulation.

The appearance of other co-immersed people would perfectly resemble their physical appearance. Everybody would display the same typical physical expressions such as posture, walk, or gestures like in reality because they would be connected to the VR world via a BMI reading their specific brain activity replicated on a physically faithful avatar. Mentally and psychologically, these avatars would be no different from their human masters as it would be ultimately the flesh and bone person driving the avatar. Social interaction would thus feel real. Alternately, one could choose to impersonate another character as a part of a virtual theatre play, or a role-playing game — maybe even taking on their (modifiable) appearance. However, the convincingness of such Robin Hoods or Arwens would entirely depend on ones acting skills.

AI-driven avatars would have more semi-generic, though designable personalities. However, being children of a multi-layered deep neural network, they would eventually display specific personality traits, making them hard to distinguish from humans. The only way of verifying their true nature would be playing a mind game with them — performing a Turing test.

Virtual AI animals would be simpler to create and sustain as their behaviour is less complex than human. Inanimate objects would be the simplest to produce. Their functioning would be purely mechanical (guaranteed by the natural law-abiding VR itself) or, in case of more complex electronic devices, a convincing simulation thereof.

To be convincing, the virtual world and its elements would have to be almost infinitely detailed in all sensory domains. Walking barefoot in a garden on a sunny summer day, the clothes we wear would have to feel soft and light, the freshly mowed grass fragrant. Looking at the Sun should be irritating (if not painful) and the texture and taste of an apple plucked from a tree would have to be just as juicy as in reality. This level of granularity represents a tremendous amount of data to be processed and transferred to the brain. Simulating the physics of every ray of light passing through leaves of the apple tree and every droplet of water on the grass, and every fragrance's turbulent flow in the air would demand unreasonable amounts of energy making the VR inefficient. An optimisation mechanism would have to be employed to cut down on the necessary computation power. Foveated rendering could serve as a source of inspiration for this mechanism. Just as gaze-direction detection in headsets provides information on what the viewer is looking at, the BMI could extract precise data on which parts of the brain are displaying elevated neural activity. This method would select which senses need more stimulation momentarily, and which can be temporarily deprived of stimuli.

Since the VR engine would be a perfect feedback loop, it would be possible to identify the immersed person's virtual location and their object of interest to further optimise the necessary data processing and flow. Thus the overall complexity of the simulation could be significantly reduced without degrading the perceived level of detail. Finer granularity would be available on a need-to-perceive and possible-to-perceive basis. Each immersion would be custom-made, yet a consensual experience of a virtual world co-created by human and machine.

Naturally, not even such an advanced VR would be rid of practical and ethical questions. Data read from the brain's neural activity, both in raw and decoded forms, would have to be legally considered as utmost private. Their processing would have to happen locally, without transmitting or sharing them with a third party. As for the data sent to the brain, the direct sensory stimulations, would have to be adjusted not to cause excessive pain, prioritising the safety and health over the virtual world's realism. A fire would feel only hot and not burn, a high-speed car crash would be only a harmless thrill, without the often fatal implications of reality. Such a safety mechanism would inevitably be an infringement of the perfect illusion — for a greater good.

However, even such an advanced BMI VR could not induce internal states directly or only do so very limitedly. Many complex internal states would occur naturally as a result of the suggestive multi-sensory immersion. A person who is afraid of heights or spiders in the physical world would react analogously to corresponding sensory stimuli in VR. People would more likely want to experience happy states connected to the brain's reward and pleasure mechanisms and feel instantly blissful. Although invasive deep brain stimulations make happiness or euphoria possible with the flip of a switch, it would have ethical implications to consider. [171] The availability of such euphoria-on-demand would make BMI VR a digital drug, which could be abused just as any legal or illegal substance. However, under medical supervision, it could have therapeutic value.

Neither could BMI VR aid direct memory creation nor rapid learning. Skills like playing a musical instrument would still have to be learned the traditional way or by playing a virtual violin in the simulation. "Brains, by contrast to the kinds of program we typically run on our computers, do not use standardised data storage and representation formats. Rather, each brain develops its own idiosyncratic representations of higher-level content.” [165] Injecting data to the brain is thus not possible and would not have the desired effect. The data needs to be processed by the brain through thought and subsequently organised into meaningful structures — information. Besides, information, unlike data, cannot be stored on any kind of media.

Even the most advanced BMI VR would not be an identical twin of reality. There would be many practical and ethical reasons to modulate its output to the brain. Beside the mentioned accidental incidents, it is beyond any doubt that intentional acts of physical violence would be a part of VR, as they sadly have been throughout human history. These would be inhibited by the same built-in safety mechanism preventing accidental injuries. Ultimately, as the simulation would not directly evoke internal states, one would always be conscious and therefore, aware of the illusion. The perfect VR immersion would be like lucid dreaming.

## 7.12. Virtual Environments for Visual Effects

So far, the efforts of combining film and cinema have not been convincing. Struggles to finding a cinematic storytelling language for VR have been in vain, and films thematising VR have not done service to VR. Perhaps a change of perception is what the blending of the two worlds needs.

Film and VR share the illusion of transporting audiences to different places and times. However, both mediums do it in fundamentally different ways. 360° video tried to bring the world of film into VR without success. In contrast, bringing VR into the world of film proves to work and perhaps is the key to merging the two.

Virtual studios are essentially massive LED walls that can replace a greenscreen or rear projection. The benefits are numerous. The desired backgrounds (or more generally environments) are already visible on set and the result is in-camera, skipping the hassle of greenscreen postproduction. The actors benefit from it too, because performing in a concrete environment is easier than imagining something abstract on a greenscreen.

Combining LED walls with practical sets is how The Mandalorian[70] TV series is being shot. The LED walls display images rendered by the Unreal Engine, a game engine used for VR. "The locations depicted on the LED wall were initially modelled in rough form by visual-effects artists creating 3D models in Maya, to the specs determined by production designer Andrew Jones and visual consultant Doug Chiang. Then, wherever possible, a photogrammetry team would head to an actual location and create a 3D photographic scan." [172] An LED wall replacing a greenscreen, front- or rear-projection is essentially only an evolution of the original idea — a painted backdrop. One could argue if such a procedure is an integration of VR into film. Certainly not in a visible manner, but being magically real is the point. The novelty of the idea lies in using a game engine to create a backdrop. It is more of technological convergence, which we are experiencing more and more often across many fields. The once-unimaginable union of cinema and television has already happened, mainly thanks to digital cameras and postproduction, which ultimately are a convergence of technologies too — of computers and cinema. Hence VR in the service of cinema is likely to walk a similar path. From a VR perspective, an LED wall surrounding a film set is a CAVE for filmmaking.

An extreme integration of VR into film was done on the Lion King[71], which was entirely shot in a VR environment created in the Unity game engine. After preproduction, which included shooting reference stills and footage on location in

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[70] Multiple directors and cinematographers, 2019

[71] Dir. Jon Favreau, DOP Caleb Deschanel ASC, 2019

Africa, “the director and his collaborators were able to define shooting setups, thus the camera position, lenses and camera moves and anything while observing the animation of the characters already playing within the virtual environment,” in VR headsets. [173] However, the actual process of shooting was very much like conventional filmmaking. The crew worked with “a virtual camera, virtual lenses and virtual lights,” [174] which were rigged and motion tracked in such a way that it imitated the way these tools are used on a physical set. Moreover, the virtual lights were modelled after existing ARRI lights to make the cinematographer’s work feel more natural to him. The crew could monitor everything in real-time on screens, as usually. The physical camera movements were subsequently encoded into the game engine and rendered as high-quality animations. “At the moment The Lion King represents probably the largest production ever made by using virtual reality as a tool for navigating an immersive shooting environment.” [173]

This method made it possible to manipulate every single element in the frame — the shape of the landscape, the trees and flowers, the Sun's position, the sky and even the performances of the digital animal actors. As everything was virtual, everything was editable to the very last detail. This is, perhaps, the cinema of the future.

# 8. Conclusions

When a distinguished but elderly scientist states that something is possible, he is almost certainly right. When he states that something is impossible, he is very probably wrong.[72]

— Arthur C. Clarke

Virtual reality started as a dream. It eventually came to life decades later thanks to numerous discoveries, inventions and technological advancements — some of them made almost a century before the original dream of Paracosma.

The technology evolved in two parallel lines. One originated in cinema and its inventor, the cinematographer Morton Heilig, envisioned it as a future multi-sensory art form: "Thus, in the future there will be two distinct forms for consuming the cinema of the future — individual and social, but with this distinction from today's individual and social consumption — each will consciously stress its own advantages. For individual consumption, quiet, uninterrupted concentration and freedom of selection are essential." [20]

The second evolutionary line was more abstract and saw the new technology as a new way of displaying data. However, that display was foreseen to become an Ultimate Display. The Ultimate Display would not only create visual representations of mathematical and real-world objects alike on a screen. It would materialise such objects in a room where a computer would control 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." [24]

[72] Clarke's first law.

Computers controlling matter and creating life-like illusions never came true and remained in the domain of science-fiction. However, VR started making its first steps into the practical world in the 1980s. Computer-generated VR became a useful tool in a wide range of computer-aided visualisations, and various training programmes for astronautics and other industries. Simultaneously, it remained a subject of research to minds who were equally brilliant and non-conform. However, it never really stood under the lime-light and was far to be considered a consumer technology despite a few attempts. The cinematic branch went silent.

The situation started radically changing in 2012. A then young computer games enthusiast posted a crowdfunding campaign ad asking for funds to develop a high-resolution and low-latency VR headset for gaming. The campaign was a surprising success, and Palmer Luckey collected almost $2.5 million, tenfold of what he asked for and founded Oculus. Two years later, before a single headset was soled, Oculus was bought by Facebook for $2 billion. This was the decisive moment when VR went mainstream. It took another two years to sell the first Oculus headset. However, VR made a stunning comeback — to the labs, living rooms and gaming arenas alike. Morton Heilig's idea of immersive films came back to the new headsets as 360° video. Unlike his immersions, the new breed was mostly monoscopic. As a novel image capture and display method, many film and media professionals attempted to create a new form of storytelling with the spherical videos — an idea already suggested by Heilig. However, a new film language was not the outcome, and the fad of 360° videos slowly sublimed.

In the meantime, research on computer-generated VR was making progress. The slowly trickling information on various research projects of technological giants like Facebook and Google, to name a few, started to create a mosaic of what their intentions with VR could be. VR stopped being seen as an isolated technology. Instead, it co-existed in a wider group of similar technologies like augmented reality and mixed reality, united under the term XR — extended reality. While the use cases of all these technologies diversified, XR slowly started converging with AI. As much as Jaron Lanier, one of the pioneers of computer-generated VR, refutes this idea, the convergence has already begun. From a broader perspective, technological convergence, especially with AI, seems inevitable in many fields. However, the combination of VR and AI can present risks previously unimaginable. The potential of using one technology to reinforce the other poses a threat to privacy, cybersecurity, and can distort the perception of reality, ultimately leading to emotional and psychological vulnerability.

From a cinematographer's perspective, the chances of cinematic storytelling in VR are zero. However, when VR is treated as a tool, it opens new possibilities to the creative process. Therefore, the cinematographer's connection to VR must stay critically openminded — ready to embrace it as a new tool if it can better the craft and simultaneously shape it to make it a better tool. Undoubtedly, lighting is an intersection of VR and cinematography, which can be approached this way.

Virtual reality manifests itself as a technology and a medium, depending on its use. Neither manifestation is yet mature, which is another emblematic trait of VR. We will always be waiting for better VR. However, the evolution of VR has already created usable tools and gives hope that these tools might become better with time.

I consider my academic research of VR hereby concluded. However, I will remain a curious observer of the developments and stay open to whatever new and meaningful union of cinematography and VR. Hopefully, someday I will have the chance of using VR in a film. That would be the moment, which would make VR feel sufficiently advanced to be magic.

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