Hochschule für Angewandte Wissenschaften Hamburg
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Master Thesis

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Virtual environments - a sensorimotor framework for perceptual design

Faculty of Design, Media and Information - Department of Media Technology
Time-dependent media: Sound, Vision, Games

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Supervisors:
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Abstract

Understanding the parameters and underlying rules of perception of high quality, complex VR environments has become more important since the availability of consumer market, real-time rendered VR applications.

VR is a medium that strongly affects the body, and due to its medium specificity, creates an experience of *place illusion* (Slater, 2009) that poses unique challenges for the environment designer.

The study develops a sensorimotor framework for the underlying rules of perception, or sensorimotor contingencies, and the basic parameters, or sensorimotor affordances, of VR environments.

It integrates the framework with a model of *perceptual design* (Ward, 2015), by describing how environmental affordances create information, simulation and spatial-temporal structuring in VR environments.

The study shows that the framework can be used to plan and analyse different types of complex VR environments, both for scientific purposes and for day-to-day design decision. It can help to clarify research questions, and integrate existing and future research on VR environments.

Keywords: virtual reality, virtual environments, sensorimotor contingencies, affordances, perceptual design, conceptual metaphor.

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1. Introduction

While real-time rendered Virtual Reality (VR) technology has been used in research labs for several decades, it has only been available as a mass medium since the introduction of consumer market headsets such as the Oculus Rift or the HTC Vive in 2015.

In research applications, the role of VR environments is often purely functional, posing few problems for the designer. But in commercial applications, be they product simulations, computer games or even scientific visualisations for a larger audience, questions of realism, quality and style become salient.

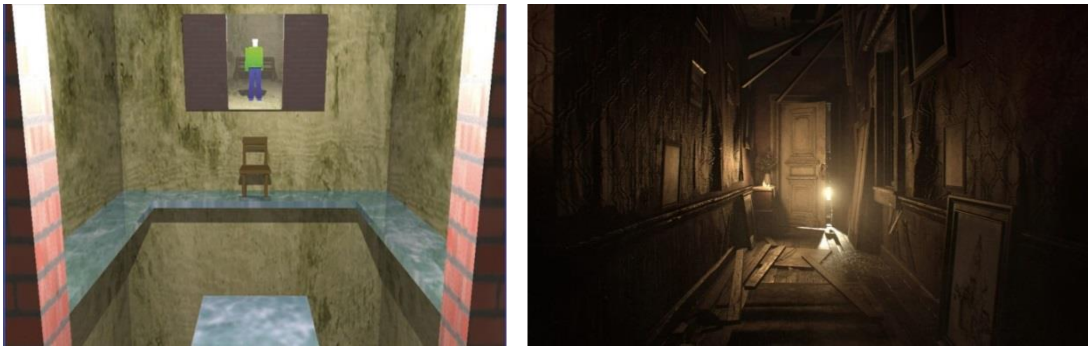
Real-time rendered VR has a strong impact on perception and physiological processes. Even early demos for the Oculus Rift Developer Kit (DK2), such as the *Rollercoaster Demo* affected user balance. The impact is explained by the fact that VR environments create “presence” or “place illusion” (Slater, Place illusion and plausibility can lead to realistic behaviour in immersive virtual environments, 2009), i.e. they are experienced as if the user were actually there.

This makes VR as a medium qualitatively different from other audiovisual media such as computer games or even 3D cinema. And while VR environments, due to their physiological and immersive impact, are in some ways closer to spatially immersive systems such as theme parks, they are not perceived and experienced identically to a physical environment.

For the environment designer, understanding the physiological processes of perception that are at work within VR environments, becomes a prerequisite for making even basic design decisions about spatial layout, surface properties or lighting. But due to the newness of VR as a mass medium, there is little research on consumer quality VR environments. Empirical studies in Human Computer Interaction (HCI) focus mainly on questions of virtual embodiment and interaction, while the crucial parameters of VR environments are less well understood. For example, a string of studies on the physiological impact of surface quality and rendering realism on immersion yields inconsistent results:

While earlier studies find no impact of surface and rendering quality on heart rate or skin conductance (Zimmons & Panter, 2003), later ECG studies show an effect of high quality rendering, including reflectivity and dynamic shadows on heart rate (Yu, Mortensen, Khanna, & Slater, 2012), and recent studies find effects on heart rate and galvanic skin response (Toczek, 2016), and blood volume pulse (BVP) and electrodermal activity (EDA) in connection with texture quality and surface detail (Hvass, Larsen, Vendelbo, Nilsson, Nordahl, & Serafin, 2017).

These divergent results can be partly attributed to the evolution of 3D technology, in combination with the fact that scientific set-ups tend to use outdated or low quality technology (Toczek, 2016) (Hvass, Larsen, Vendelbo, Nilsson, Nordahl, & Serafin, 2017), but questions about the impact of surface “realism” on immersion, and the underlying rules of perception within VR environments remain.



High quality surfaces in a research set-up (Yu et al. 2009) and in *Resident Evil 7* for PlayStation VR (2017).

Another methodological problem that limits the practical applicability of such studies is that they usually test one isolated environmental factor, whereas environments are always perceived as multifactorial clusters. Understanding the underlying rules and parameters that are at work in the highly complex and vast environments of current VR games such as *Resident Evil 7* for Playstation VR (2017) by isolating them and testing their effect on users seems impractical. And even within a "neutral" environment, several parameters have an effect on perception, and potentially on reaction and behaviour: a completely white room might carry futuristic or ethereal associations, while a reduced, simple environment could evoke the unreal, "safe" world of cartoons, where risks have no consequences.

Since the late 1990s, cognitive approaches in architecture and media studies have begun to develop tools for analysing perception and design processes within complex environments. For this they make use of methodologies from phenomenology, based on Merleau-Ponty's *Phenomenology of Perception* (1962), with a focus on the sensory, synaesthetic and physical experience of space and atmosphere; *Ecological Theory*, based on James J. Gibson's work about natural perception and the interconnectedness of body and environment (Gibson J. J., 1986), and cognitive sciences and neurobiology. For an overview see: (Grodal, 2005), (Fahlenbrach K. , 2010).

They work with a "common capacity" approach to design, meaning the assumption that media and the arts address and exploit the properties of the human sensory and cognitive system (Bundgaard, 2014). According to that approach, both creation and perception processes are informed by "intercorporeality", i.e. the shared experience of having a human body within a physical environment (Gallese & Gattera, 2015). These body-centered approaches seem appropriate for a medium that impacts the body as strongly as VR.

The central role of the body is not surprising if one considers the medium specificity of VR, i.e. the way in which the material characteristics of the technology constitute both content production and perception. VR systems provide technology not only for 360° stereoscopic vision and sound, but also for rotation and translation tracking of real-time self-movement. Taken together, these technologies are the prerequisite for the use of *sensorimotor contingencies* (SMC), i.e. the implicit rules of how self-movement is used for perception. Slater identifies sensorimotor contingencies as the source of "place illusion" in VR (Slater, 2009).

VR can be described as a sensorimotor medium the same way as film is an audiovisual medium, and as computer games are an interactive medium, referring both to perception and to creation. Not only does the user see and hear a film, or interact with a game; the designer creates and works with images, sounds, and interactions, i.e. they form the raw material of the medium.

But how does one design with sensorimotor contingencies?

Recent cognitive research on design processes has begun to ask questions about how designers create perceptual meaning (Bundgaard, 2014). Mark Ward develops a model of *Perceptual Design* for sound design that can be adapted for other media techniques, such as editing, lighting or set design (Ward, 2015). As he defines perceptual design as all audiovisual design techniques that affect the sensorimotor system to create perceptual meaning, his model seems meaningful for understanding VR environment design.

Purpose of the study

The purpose of this study is to establish a framework that allows a first overview of the main parameters and underlying rules of perception of VR environments. The framework is set up in such a way that it can be expanded in the future.

It includes basic spatial environmental parameters such as layout, surface properties and lighting, and adds additional information such as animation, sound and haptics, where they directly affect spatial parameters. Self-movement as a central sensorimotor contingency that constitutes spatiality is also discussed.

The framework not only addresses how perception generates information within VR environments, but also how this information forms the basis for additional simulation and spatial-temporal structuring through a perceptual design process.

Thesis Outline

To develop the framework, Part 2 discusses the media specificity of VR in the context of audiovisual, interactive and spatially immersive technology.

It delineates Slater’s concepts of *place illusion* (PI) and *plausibility illusion* (Psi), and his observation that place illusion is constituted by the sensorimotor contingencies that are provided by the VR technology.

Following his approach, sensorimotor models of perception are reviewed, including a sensorimotor loop between the body of the observer and the environment, and the importance of self-movement for perception is discussed.

With Gibson’s model of environment perception in mind, Part 2.2 introduces the term *sensorimotor affordances* (SMA) to describe environmental factors within an environment that are part of a sensorimotor loop. It uses the concept of sensorimotor affordances to revisit earlier studies on surface quality and rendering realism in VR, and concludes that the model of sensorimotor affordances can be used to explain the inconsistent study results and possibly allow making first predictions on how different environmental factors affect user perception in VR.

Part 3 discusses the consequences of this insight for VR environment design, and shows how it can be applied to build environments with sensorimotor affordances.

It explains in what way the sensorimotor functions of the body, mediated through VR technology, generate information about the self, the environment and self-movement. Part 3 also introduces a framework for perceptual design in VR to understand how this information forms the basis for simulation and spatial-temporal structuring. It analyses the basic parameters of VR environments to demonstrate how they can be utilised as sensorimotor affordances, generating information, simulation and spatial-temporal structuring.

Part 4 presents four virtual environments for different real-life purposes, i.e. a technical visualisation of a Wind Turbine for a lay audience, an interactive visualisation of a Fin Whale skeleton for a museum, a research application for walking-in-place and rotation, and a horror experience environment.

Part 5 demonstrates the versatility and robustness of the methods established in Part 2 and 3, by using them to analyse the sensorimotor affordances of the different environments presented in Part 4. Additionally, it integrates early user reaction into the discussion.

The analysis provides insights into how position, scale, layout and self-movement interact in VR environments, how the vestibular sense is affected by animated rotation and movement, how surface properties and lighting relate to interaction, and what role haptics play for VR environments.

Part 6 concludes that the sensorimotor framework for VR environments provides a functional overview of the underlying rules of perception (or sensorimotor contingencies) in VR, and of the basic parameters (or sensorimotor affordances) of VR environments. It cannot replace studies that investigate isolated environmental factors, but it can help to identify and clarify research questions, and integrate existing and future research.

It shows that the sensorimotor framework can offer guidelines for VR environment designers, and suggests that the methods developed in this thesis might be adapted for the analysis of complex environments in other areas, for example theme park design or game design.

In summary, the thesis understands itself as a first attempt at formulating a theory of perceptual design for VR, and as such hopes to contribute to a developing corpus of scientific investigations into design processes.

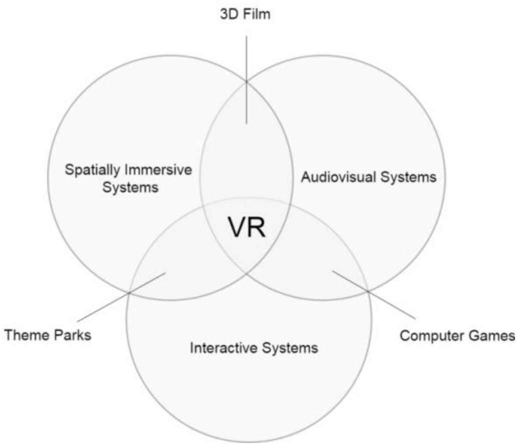
2. Theoretical background and terminology

2.1. VR Technology

In general, design techniques in media, design and the arts are generated and determined by a system's technology. Just as editing as a film technique developed only because celluloid film can be cut and pasted, camera movement as a film technique was only developed when cameras became less heavy and could be moved. Therefore, understanding the potential techniques of VR requires a closer look at VR technology.

Current desktop consumer VR combines the technologies of audiovisual and interactive systems, such as film and computer games, in that it contains a camera and display, a sound system, real-time rendering, 3D content, and controller technology. As a result, environment design for VR is often treated as an extension of film or game design.

But VR is also a spatially immersive technology with 360° stereoscopic vision and body tracking that creates a unique sense of spatial illusion and "presence". VR environments are experienced "from within", not through the frame of a screen.



VR at the intersection of spatially immersive, audiovisual, and interactive systems (source: author).

SYSTEM TYPE	TECHNOLOGY	OUTPUT
spatially immersive	Virtual environment, body movement/tracking	Space/place illusion, self-movement
audiovisual	Camera, display, sound system	Vision, sound
interactive	Real-time engine, interface/controller	Real time movement, interaction

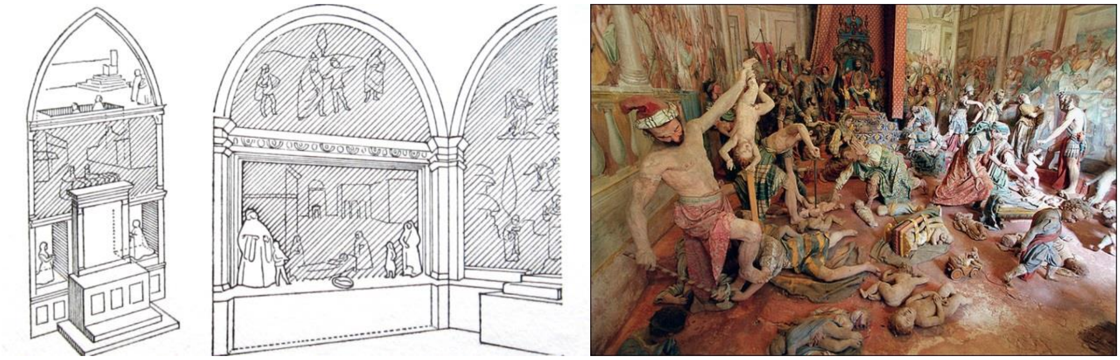
2.1.1. Spatially immersive technologies

According to Oliver Grau (Grau, 2003, p. 5ff.), spatially immersive systems, i.e. technologies that create illusionary, virtual spaces, existed long before the invention of photography, or even before the discovery of central perspective, though they are somewhat underresearched. Central perspective is often seen as the basic requirement for the depiction of illusionary depth in 2D imagery, culminating in trompe l'oeil painting. But other methods for creating virtual space were often preferred, as they provided stereoscopic depth perception, 360° view and self-movement. Grau lists a number of early spatially immersive installations such as the fully painted panoramic rooms in Roman villas and medieval castles, architecture with forced perspective, and 2.5D installations in churches and theatres.

2.5D is a mix of 2D and 3D elements that is still heavily used in computer games and animation, but also in today's haunted houses and theme parks. In 2.5D, 3D elements are placed in the foreground to provide strong motion parallax, and to extend the virtual space into the physical space of the visitor. 2D elements are used for expanding background elements where motion parallax is less pronounced. 2.5D can be used both in 360° panoramas and in dioramas that provide a narrower field of view.

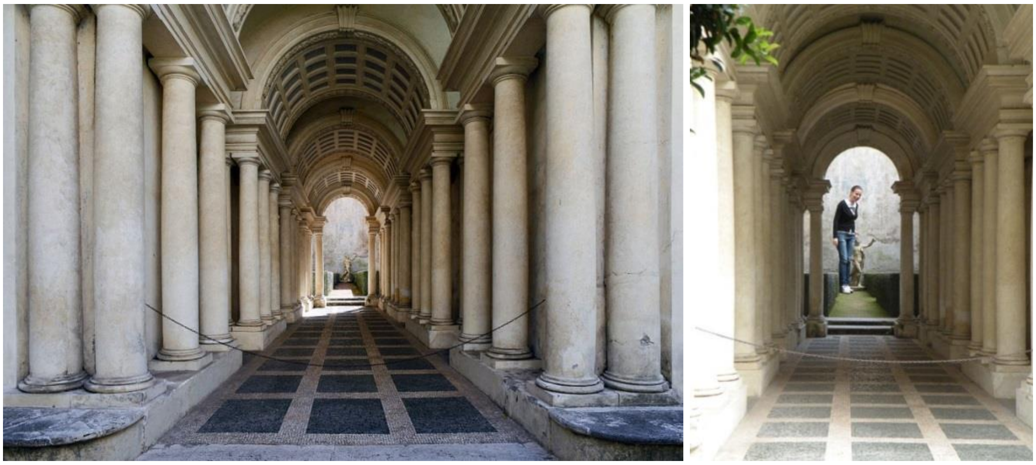
Successors of private panoramic rooms were the massive public 360° panoramas of the 19th century which could contain 3D foreground elements such as trees or rocks, animated day and night simulations, and sound and smell effects. Apparently, in some visitors this caused a sensorimotor disconnect and "panorama sickness", with symptoms similar to VR sickness (Grau, 2003, p. 64).

The invention of stereoscopic drawings by Sir Charles Wheatstone in 1838 possibly preceded the invention of photography (Brooks 2017). Stereoscopic images create a stronger illusion of virtual depth than trompe l'oeil paintings because they capture two different eye positions, thus "capturing motion"; but they are still one-directional and static, meaning they do not include the optic flow of environment movement or self-movement.

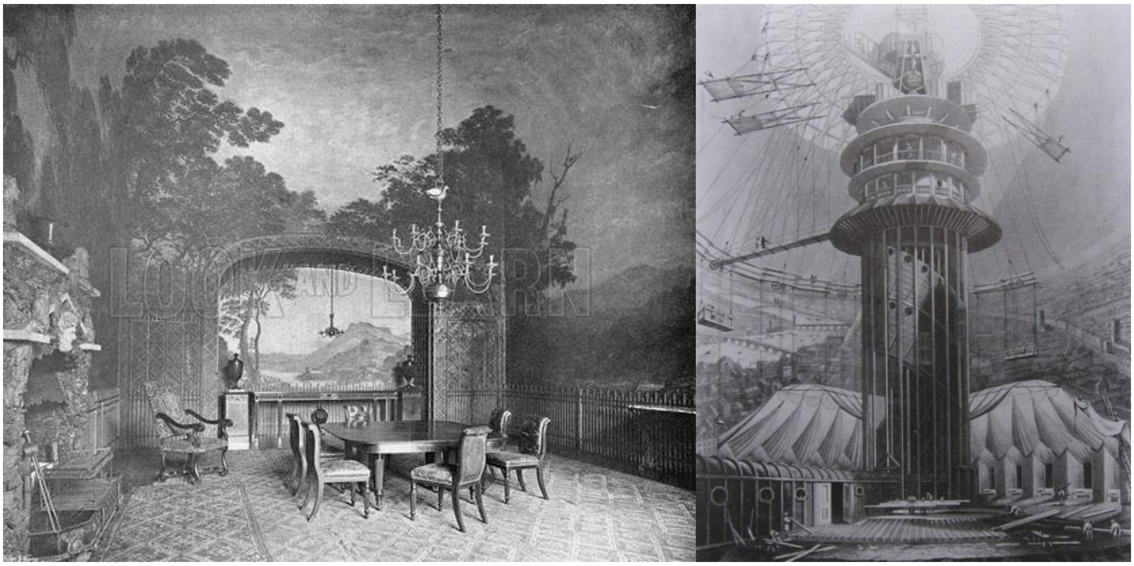


2.5 Art in St. Trinita (source: Phillipot 1972), Sacro Monte di Varallo (http://www.sacromonte-varallo.com).

Trompe l'oeil choir in Santa Maria presso San Satiro (Milan) (Source: Wikimedia commons).



Forced perspective at the Palazzo Spada (source: Wikimedia commons).



Landscape room 1793 (source: Grau 2003), Colosseum Panorama in London 1829 (source: Kemp 1990).

Modern panorama by Yadegar Asisi (source: http://www.asisi.de/panoramas).

Environment elements moving “out of the screen” (source: *L'arrivée d'un train en gare de La Ciotat*, 1896, *Creature from the Black Lagoon 3D*, 1954).

The camera obscura as a natural phenomenon that shows both spatial depth and environment animation on a 2D surface was probably always known. But it was the invention of light sensitive film that first allowed the recording optic flow on a 2D surface. Optic flow in combination with central perspective was soon exploited as a source for illusionary spatial immersion. Either the camera moved within the environment, creating an illusion of self-movement. Or objects within the scene seemed to move into the direction and physical space of the observer, for example when the *film L'arrivée d'un train en gare de La Ciotat* (1895) by the Lumière brothers allegedly caused a panic in the audience.

Stereoscopic cinema combines optic flow and stereoscopy as early as 1922 (Zone, 2007), increasing the effectiveness of environment elements that “jump” out of the screen. But by definition, stereoscopic film is pre-rendered, restricting actual self-movement of the observer, which in turn reduces spatial presence.

IMAX and other 360° film systems allow for head rotation, but the viewer’s movements along the x,y and z axis are still competing with the camera’s movements. The conflict is somewhat diminished by the use of panoramic films that focus on background vistas and middle ground elements, but with few foreground elements, a set-up that creates less motion parallax. Stereoscopic 360° film achieves a more natural vision through head rotation, but still lacks real-time tracking of translation within space.

Interactive media such as computer games make use of real time render engines to enable “self-movement” of the camera or an avatar within a 3D environment, with the resulting optic flow. Some interactive media can cause sensations of physical immersion, for example first person computer games that show proprioceptive elements of the virtual body, such as arms and especially legs. When the user is seated close to the display or uses a display set up that covers peripheral vision, motion sickness can occur (see reviews of *Mirror’s Edge*, USA 2008). Computer games are monoscopic, i.e. the camera renders only “one eye”.

First person view with proprioceptive elements (source: Mirror’s Edge, 2007).

Controller technology allows for real time interaction with the game content, i.e. the user can not only move in real time, but also influence and control what happens on the screen.

While keyboard and mouse enable only a very abstract mapping of interaction, for example the pressing of WASD keys for body movements, other controllers such as gamepads or WII controllers with body tracking can transfer more naturalistic movements of the hands, arms or the full body into the virtual environment.

Current consumer VR solutions combine head mounted displays (HMD) with stereoscopic vision and 360° view, and real-time rotation and translation tracking for intense sensations of spatial presence and physical immersion, including illusions of self-motion, loss of balance and motion sickness.

2.1.2. Presence and Place Illusion (PI)

VR is often described as a medium that creates “presence”. But the term is probably the most used and the least defined in VR literature. It was originally coined to describe a sense of extended body perception during robot operation (Slater, Place illusion and plausibility can lead to realistic behaviour in immersive virtual environments, 2009). Over the years it came to mean a range of different things in non-immersive and immersive contexts, for example presence when playing a computer game or presence while reading a novel.

To specify the term, presence can be operationally defined as the extent to which observed behaviour is similar to what it would be in an equivalent real-world situation (Garau, Friedman, Widenfeld, Antley, Brogni, & Slater, 2008). Pankaj Kannah and colleagues extend this to include all responses to VR “as if it were real” (Khanna, Yu, Mortensen, & Slater, 2006):

- low level physiological responses
- behavioural responses
- emotional and cognitive responses
- the sense of having ‘been there’

To define the elusive sense of having ‘been there’, Slater distinguishes immersive systems of different orders of presence, depending on the sensorimotor contingencies they afford (Slater, Place illusion and plausibility can lead to realistic behaviour in immersive virtual environments, 2009). Sensorimotor contingencies are defined as lawful regularities of the sensorimotor flow, i.e. the implicit rules that we know concerning how to use our bodies to perceive the world, and how sensory stimulation varies depending on the movement of the perceiver, for example bending around an object to see its backside (O’Regan & Noë, 2001).

Slater defines an immersive system as being of a higher order when it can be used to simulate a second system, but not vice versa, e.g. one can play a computer game on a PC display in VR, but not vice versa. Only first order systems create actual place illusion (PI), that is, the involuntary, automatic and immediate illusion that the body is “really there”. Place illusion occurs when the sensorimotor contingencies of the system are similar to the sensorimotor contingencies of physical reality. If that is the case, for the brain, the simplest hypothesis is to assume that the user is “actually there” inside the virtual environment (Yu, Mortensen, Khanna, & Slater, 2012). Place illusion is mainly afforded by the technology, in this case the HMD and the tracking system, which allow users to utilize their bodies to carry out sensorimotor acts of perception in real time.

Sensorimotor functions	Reality	Vive, Rift	Panorama 360°	FIlm	3D Film	3D games
depth perception (monocular)	x	x	x	x	x	x
stereopsis	x	x	x		x	
head rotation (camera)	x	x	x			(x)
optic flow (environment)	x	x		x	x	x
self-movement/body (camera)	x	x	x			(x)
hand interaction	x	x				x
hearing	x	x	x	x	x	x
touch	x	(x)				(x)

Place Illusion is therefore not a cognitive but a perceptual phenomenon, and as such, automatic. As a qualia associated with sensory illusion, Slater proposes to define it as binary: Either you get the illusion or you don’t. When breaks of place illusion occur, this happens due to technological problems (lost tracking etc.), which temporarily lower the order of the system.

To account for experiences of partial presence, Slater describes place illusion as domain specific. For example you can experience place illusion within a VR environment on the visual level, but hear sounds from the physical environment that break the immersion on the auditory level.

Slater’s definition of VR as a sensorimotor illusion is closely related to the unifying hypothesis of Mark Changizi and colleages, explaining a high number of classic optical illusions by sensorimotor and neural mechanisms of completion (Changizi, Hsieh, Nijhawanc, & Kanaib, 2008).

2.1.3. Plausibility Illusion (Psi) and levels of immersion

According to Slater, the degree or intensity of immersion can only be compared within orders of presence, as each order creates experiences that are qualitatively different from the others, e.g. the experience of a 3D film is of a different qualia and order of presence than a HTC Vive experience that includes real time rendering and tracking.

To account for differences of immersion when comparing similar applications, Slater (2009) distinguishes between *place illusion* (PI) and *plausibility illusion* (Psi).

Lower degrees of immersion are caused by insufficient plausibility within the virtual environment. One VR game can be less immersive than the other, even though both share the same technology, and both create place illusion.

But while the technological requirements necessary for place illusion are relatively well researched, and PI is easily achieved with current consumer technology, requirements and best practices for plausibility illusion are less clear (Bergström, Azevedo, Papiotis, Saldanha, & Slater, 2017)

Plausibility illusion is a very broad term that has been equally used to describe plausible interaction with a virtual avatar, rendering of real time shadows, and ambient sounds (Yu, Mortensen, Khanna, & Slater, 2012) (Bergström, Azevedo, Papiotis, Saldanha, & Slater, 2017) (Slater, Place illusion and plausibility can lead to realistic behaviour in immersive virtual environments, 2009).

Richard Skarbetz and colleagues stress the importance of coherence for plausibility illusion (Skarbez, Neyret, Brooks, Slater, & Whitton, 2017). Coherence seems to have a similar function as "world building" for computer games. An environment may be sheer fantasy and even have an alternate physicality such as low gravity, but still be perceived as "real" – provided it follows coherent laws (Bergström, Azevedo, Papiotis, Saldanha, & Slater, 2017). Rovira et al. list the following requirements for plausibility illusion: The environment must be correlational, i.e. the actions of the user must elicit responses from the environment, it must be self-referential, i.e. elements within the environment refer directly to the user, and it must be credible, i.e. the behaviour of the environment must be consistent with the user's prior knowledge (Rovira, Swapp, Spanlang, & Slater, 2009).

A combination of PI and Psi causes a "response-as-if-real", but users are always cognitively aware that they are inside an illusion. This can lead to behaviour that differs from real life behaviour, for example experimenting with dangerous situations such as heights or zombie attacks (Garau, Friedman, Widenfeld, Antley, Brogni, & Slater, 2008) (Slater, Place illusion and plausibility can lead to realistic behaviour in immersive virtual environments, 2009).

2.2. Sensorimotor models of experience

Another often used but little defined term for immersion in VR is "experience". When discussing experiences, it is difficult to avoid an "explanatory gap" (Levine, 1983) between descriptions of the physiological processes involved in an experience, and descriptions of the phenomenal quality of experience. For example, it is a challenge to explain why visual brain activities are associated with visual experience. For how can a neural code give rise to an experience?

Several cognitive theories address this issue by employing "embodied" approaches, i.e. by considering the foundational importance of sensorimotor patters of interaction with the environment for experience (Degenaar & O'Regan, 2015). O'Regan and Noë formulate a sensorimotor model of perception, stating that perception is the implicit knowledge of the effects of self-generated movements on sensory signals, i.e. the exploration of the world mediated by the knowledge of sensorimotor contingencies (O'Regan & Noë, 2001). "Instead of assuming that vision consists in the creation of an internal representation of the outside world whose activation somehow generates visual experience, we propose to treat vision as an exploratory activity.” (O’Regan & Noë, 2001, p. 940). This model can explain a high number of so far unexplained phenomena of perception, for example visual “filling in”, visual stability during eye movement, change blindness, sensory substitution, and colour perception. The approach is supported by experiments in sensorimotor adaption.

2.2.1. Self-movement and the sensorimotor loop

The importance of self-movement for environment perception is reinforced by the ambiguous and partial nature of the sensory information that is available at any given moment, for example due to occlusion (Bütepage, 2016, p. 10ff.). Additionally, both the body and the environment are non-stationary. But while we usually cannot control how our environment moves, we can always control and know our own position relative to our environment, through self-motion such as eye, head and body movement (Changizi, Hsieh, Nijhawanc, & Kanaib, 2008, S. 73ff.). Sustained self-movement generates a constant flow of data about the spatial status of our environment, proving Edmund Husserl’s claim that “[a]ll spatiality is constituted by movement” (Husserl, 1973). Even eye saccades and small head movements increase depth and velocity perception or object recognition. Cognition through sensorimotor contingencies is theorized as an active and multisensory probing of the environment and as such a bidirectional loop (Kaspar, König, Schwandt, & König, 2014).

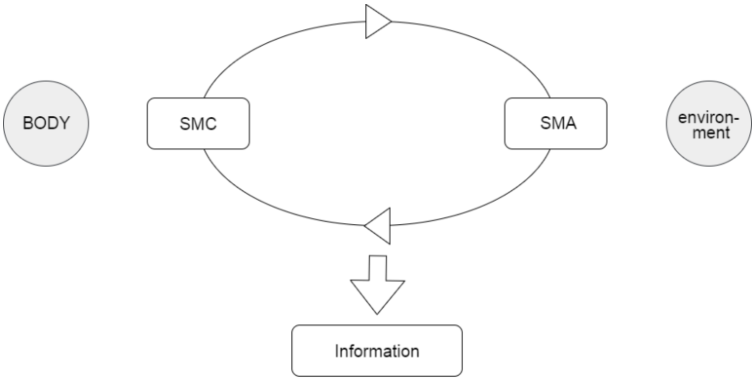
Sensorimotor contingencies can also be defined as learned action-effect mappings: By using sensorimotor contingencies, environmental factors, including physical relations and laws can be identified and integrated (Bütepage, 2016, p. 11). This then allows the prediction and planning of future movements. For this reason, sensorimotor contingencies are successfully applied in robotics and artificial cognitive systems (Maye, Trendafilovy, Polaniy, & Engel, 2015). Body augmentation can even cause the learning of new sensorimotor contingencies (Kaspar, König, Schwandt, & König, 2014).

2.2.2. Sensorimotor Affordances (SMA)

O’Regan and Noe distinguish sensorimotor contingencies (SMC) that are inherent in the physiology of the body, such as eye or ear position, from those that are determined by the attributes of the environment. This includes the size, shape, volume, texture and colour of objects, in addition to their position, distance, rotation, but also gravitation, the changing light situation, the sound reflectivity of an environment, and so on (O’Regan & Noë, 2001).

Loosely drawing on Gibson’s model of environment affordances, i.e. the perceived action possibilities inherent in objects and environments (Gibson J. J., 1986), I propose to distinguish all environmental sensorimotor contingencies by the term *sensorimotor affordances* (SMA).

Following that definition, the sensorimotor loop consists of the sensorimotor contingencies of the body in a constant feedback loop with the sensorimotor affordances of the environment.



Sensorimotor loop (source: author).

If we assume that environmental parameters function as sensorimotor affordances within the sensorimotor loop, the question arises as to which parameters function that way and why. And how does all this relate to VR environments?

Yu et al. begin to address these problems when they observe an increase of physiological responses in reaction to real-time rendered reflections and shadows, indicating an increase of presence within the VR environment. They attribute their findings to an increase in plausibility illusion, due to a not otherwise specified correlational reaction of the environment to the user's behaviour (Yu, Mortensen, Khanna, & Slater, 2012). But what does correlation mean here?

I propose that what they describe is not a random, but a lawful correlation between sensorimotor affordances of the environment (surface reflectivity) and sensorimotor contingencies of the body, specifically self-movement, forming a sensorimotor loop. When the user actively changes her position and viewing angle within the virtual environment, the reflections move according to specific optical and physical laws.

This definition of environmental correlation as a sensorimotor loop induced by self-movement can also clarify the inconsistent results of studies about surface quality and detail: an increase in physiological responses was observed by Hvass et al. and Tokcek when they tested the effects of increased texture quality and surface detail (mesh detail) (Hvass, Larsen, Vendelbo, Nilsson, Nordahl, & Serafin, 2017) (Toczek, 2016). But at the same time, earlier studies seem to indicate that different degrees of surface quality do not influence physiological responses (Zimmons & Panter, 2003).

The apparent contradiction might be explained by the fact that a highly detailed surface constitutes sensorimotor affordances that cause an increase of opportunities for sensorimotor contingencies, specifically self-movement, and the low poly surface does not. Surface detail self-occludes at changing degrees and angles in relation to the self-movement of the user. A flat texture does not self-occlude or self-shade in relation to real-time self-movement, and therefore provides fewer sensorimotor affordances. But real-time reflections or specularity on a flat surface function as sensorimotor affordances that react to self-movement, and as expected, studies demonstrate that they increase physiological responses (Yu, Mortensen, Khanna, & Slater, 2012).

As this example has shown, the sensorimotor loop seems to be a functional model to identify the underlying rules of perception (sensorimotor contingencies) and the corresponding parameters of VR environments (sensorimotor affordances), to understand how they interact, and possibly to predict how they will affect presence within a VR environment.

If egocentric self-movement within a three-dimensional environment is the sensorimotor contingency that distinguishes real-time VR from other audiovisual media, and if real-time VR creates consistent place illusion, but other audiovisual media do not, then self-movement is probably the central sensorimotor contingency of VR. That means that environmental affordances that react lawfully to self-movement will probably increase presence. They also allow the user to generate information through a sensorimotor loop.

Part 4 discusses the consequences of this insight for VR environment design, and shows how it can be applied to build environmental affordances that generate information by inducing a sensorimotor loop. It also explains how this information can be used as the basis for simulation and spatial-temporal structuring in VR environments.

It integrates the findings to develop a framework of the rules of perception, or sensorimotor contingencies, and of the basic environmental parameters, or sensorimotor affordances, of VR environments.

3. A sensorimotor framework for VR environments

"VR is based on finding ways to present what should by all rights be inadequate equipment in a way that somehow meets the expectations of the human nervous system. Our field can be considered as the study of highly advanced stage magic without the stage." Jaron Lanier quoted in: (Hale & Stanney, 2015, p. xv).

As I have shown in Part 3, sensorimotor contingencies, and specifically self-movement, are central for presence in VR. To generate information, they loop with sensorimotor affordances within the environment. Therefore, the environment design should somehow implement sensorimotor affordances that react lawfully to the sensorimotor contingencies provided by the VR technology.

But as I have discussed before, environments in consumer VR are not just test scenarios for single-factor studies; usually they are complex scenes with numerous parameters that interact for specific purposes. While older media systems developed techniques for manipulating perception and structuring content over the course of several decades, VR as a high quality consumer system is only a couple of years old.

And, as we have seen, while VR shares several technologies with older media systems, VR's media specificity, namely its ability to create place illusion, prevents that media techniques are transferred 1:1 from other audiovisual or interactive media to VR. To get an idea of what media technique for VR could mean it is necessary to first understand how media techniques in general function.

3.1. Perceptual design

Peer F. Bundgaard defines artworks, and by extension VR environments, as objects with an enhanced semiotic function, which convey meaning not primarily through mechanisms like symbolism, but in a direct, perceptual sense (Bundgaard, 2014). Surprisingly, while there are numerous studies on the "higher" mechanisms of art and media creation, for example narrative or symbolism, little systematic research investigates the underlying perceptual techniques that Bundgaard is referring to. The bulk of the existing literature on art and media technique is non-systematic and mainly consists of pragmatic, single-case observations or rules-of-thumb by practitioners and producers (Grodal, 2005) (Poland, 2015).

Mark Ward develops a model of *Perceptual Design* for sound design that can function as a blueprint for systematising research on media technique. According to his model, perceptual design refers to all audiovisual design techniques that affect the sensorimotor system to create perceptual meaning. That definition includes conventional media techniques such as camera, editing, lighting, set design, but also environment design for VR (Ward, 2015).

Perceptual design influences core affect and body sensation through pre-cognitive, pre-attentional and nonconscious mechanisms, and creates the "proto-narrative" foundation on which narrative is built. An important mechanism of perceptual design is the multi-modal simulation and abstraction of physical experiences. In a central observation, Ward describes how audiovisual media "reverse-engineer" affect by simulating the physiological effects that accompany the affect (Ward, 2015, p. 182ff.). A well-known example is the sudden slow-motion and complete silence in dramatic film situations, simulating the physiological effects of shock, such as numbness and a slowing down of time. Another example is the acceleration of drums in soundtracks that simulates, and possibly stimulates, an accelerated heart rate.

Building on Ward's model, I propose that perceptual design in audiovisual and spatially immersive media has three main functions:

I. Providing sensory information, e.g. about the position or movement of an object or sound source.
II. Simulation, e.g. of physiological effects, valences or affects, e.g. simulating excitement through sound.
III. Spatial-temporal structuring, e.g. creating orientation and duration with techniques like camera movement or film editing.

Simulation can make use of the following mechanisms:

a. Completion or "filling-in": the simulation of sensory input by another input, for example impact sounds that simulate haptic impact; the simulation of heat through red light, etc.
b. Action activation and neural "mirroring": observing a film character's actions and affects induces neural action activation in the observer, etc.
c. Cognitive mapping: the mapping of valence and structural meaning through factors such as lighting, for example light=safe/good, dark=dangerous/bad, etc.

I show how this model can be adapted for VR environment design to understand how the generation of information, simulation and spatial-temporal structuring function within VR.

3.2. Sensorimotor information

In a physical environment, basic types of information are generated by the use of sensorimotor functions:

- Self-perception: by use of the somatosensory system, including proprioception, haptics, vision and vestibular sense.
- Environment perception: using vision, sound, haptics, chemical senses, and self-movement.
- Perception of movement: using proprioception, vestibular sense, and self-movement.

But as we have seen, VR technology restricts and shapes sensorimotor functions and provides only reduced sensorimotor information. Some sensory input is distorted (e.g. distance perception), incomplete or missing (e.g. touch, chemical senses), and needs to be compensated for or simulated in some way. Or it may be contradictory to the input from the physical environment (e.g. somatosensory system, vestibular sense).

3.2.1. Self-perception

The somatosensory system includes all receptors for the position of different organs, muscles, joints, and also the sense of touch, pain and temperature (Blade & Padgett, 2015). This data forms the basis for a neurological body schema that includes form, size, position, and boundaries of the body. This map is plastic, i.e. in the course of a lifespan it can integrate changes such as growth, or weight gain or loss. In cases of sudden limb loss, the body map can fail, giving rise to phenomena such as "phantom limb".

First proposed by Head and Holmes in 1911, their early theory of body schema already stated that it can integrate clothes and tools that are regularly used (Holmes & Spence, 2006, p. 15).

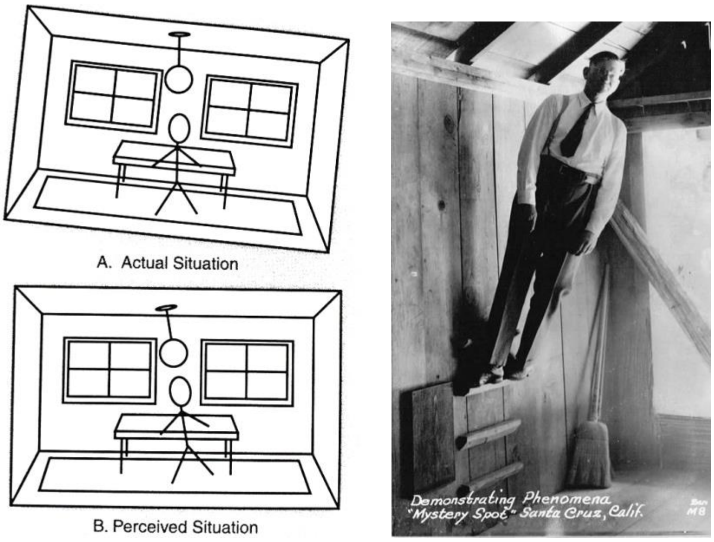
Computer games make use of the plasticity of the body map to integrate controllers, virtual hands or virtual bodies (Gregerson & Grodal, 2009).

The body's position in space is perceived through proprioception, containing the kinaesthetic sense of muscle and joint position, and the vestibular sense hosted inside the inner ear. The receptors of the vestibular sense react to gravity, change of direction and acceleration (Palmer, 2002, p. 334ff.). Spatial orientation is always established relative to gravity, but gravity is perceived via the vestibular system as well as haptic input. Shifts of the centre of gravity, for example standing on one leg, will increase haptic pressure ("weight") on some body parts, while reducing it on others.

Proprioception also integrates visual data, with far-reaching consequences for VR design (Blade & Padgett, 2015, p. 30ff.). Specific retinal and cortical cells in the eye are primed to detect a frame of reference that is parallel or perpendicular to gravitation (Palmer, 2002, p. 151ff.). As such, the field of vision forms a body-centered frame of reference for orientation.

The visual frame of reference can completely overpower proprioception through visual capture (Palmer, 2002, p. 346). Artificially tilted rooms, as those in fun houses of amusement parks, do not create a sensation of a "wrong" room but of a "wrong" visitor. Visitors believe themselves to stand in an unnatural angle while the chandelier seems to hang diagonally from the roof (Palmer, 2002, p. 336). Physical sensations of loss of balance and fear of falling can be induced by visual input alone, for example when looking down from great height in a physically stable position such as the "visual cliff", a thick pane of glass over a chasm. Infants from the age of 6 months and animals have been shown to avoid the visual cliff (Gibson & Walk, 1960).

Visual information about movement can even induce illusionary somatic sensations of self-motion, or *vection*. These physical sensations are well known from sitting on stationary trains while another train is passing by the window. Moving or swaying walls can induce swaying in a test subject, as visual information about verticality is used for postural control (Hansson, Beckman, & Håkansson, 2010). Sensations of swaying and falling become more acute in the absence of strong visual cues that support visual postural control (Strang, Haworth, Hieronymus, Walsh, & Smart, 2011).



Tilted room illusion (source: Palmer 2002), "Mystery Spot" Santa Cruz (source: www.mysteryspot.com).

Through a process of constant multimodal revision, the human body can adapt to changing physical parameters of environments surprisingly fast, no matter if the alternate environment actually exists or was created through the use of distorting lenses and similar devices (DiZio & et.al., 2015) (Wann, et al., 2015). Free self-movement within an alternate environment increases the speed and depth of the adaption (Palmer, 2002, p. 151ff.).

If we take these physiological factors into account, a number of possible consequences for VR design come to mind: Head-mounted displays (HMD) and headphones suppress visual and audio information about the physical environment, but haptic, somatosensory and proprioceptive information from the body cannot be suppressed. The sense of the body's orientation relative to gravity, and haptic information such as contact with a chair or floor is the basis on which VR is experienced. Change of direction, rotation and acceleration, or a lack thereof, is registered by the vestibular system. It can be overridden to a degree by visual capture, even causing illusions of self-motion. But vection has been identified as an important factor for motion sickness (Keshavarz & et.al., 2015).

3.2.2. Environment perception

The human visual apparatus consists of two eyes that work together by providing images from two slightly different positions. From them, the brain processes a unified, spatial vision. Since first described in 1028 by Ibn al-Haytham in his *Kitab al-Manazir* (Optics), the stereoscopic parallax between the two images is interpreted as the source of depth perception. While most animals have eyes on each side of the head, humans, apes and some predators have frontal eyes. Eyes on the side of the head create a 360° field of view with only a small stereoscopic overlap in the front and back of the head. Frontal eyes have a smaller field of view but a larger stereoscopic overlap. The narrower field of view is compensated for by head movement.

Stereopsis mainly affects foreground and middle ground objects, but is barely visible in far distances. Changizi argues that the effect of stereo vision for depth perception is somewhat overstated, as people who have lost an eye, or animals with small stereoscopic overlap can still navigate space effortlessly. Also, it is possible to correctly interpret depth on 2D surfaces such as computer screens, as we can navigate 3D space with an avatar when we play computer games. According to Changizi, visual overlap has another significant function: binocular vision allows animals to “see through” near-range small obstacles such as twigs and leaves. This becomes important when moving fast through obstacles, for example when jumping from tree to tree. In 3D computer games, which are by nature monocular (one eye/camera), such stereoscopic see-through vision is not possible, which causes problems when the player attempts to move around in an environment that is rich in small obstacles (Changizi M. , 2010, p. 73ff.).

Eye distance plays an important role in scale and distance perception. By artificially changing eye distance, the relative size of an environment, and distance perception in general, is affected, i.e. the larger the eye distance (hyperstereopsis), the smaller the environment is perceived, and vice versa (Priot, Vacher, Vienne, Neveu, & Roumes, 2018). This effect can be explained by the change of angles in the optic array and by the changing extent of the area that is affected by stereopsis. A change of eye distance causes over- and underestimation of distances or object sizes.

Several studies have shown that distances in VR are judged differently than in physical environments, though the cause does not seem to be fully established (Lin, 2015).

Generally, environmental scale seems to be calculated in relation to the size of the perceiver, mainly from the height of the eye position and the eye distance. The length of steps probably plays a role for relative distance calculation, for example an artificial change of step length has been shown to cause over- or under-reaching in pathfinding ants (Collett & Graham, 2010).

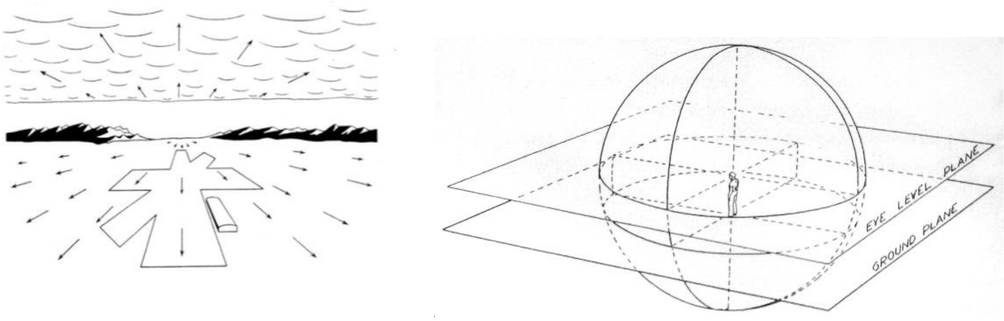
Depth perception without stereopsis is also possible through inferences that depend on laws and physical properties of the environment, the so-called monocular cues. Monocular cues seem to be processed pre-cognitively as they can trigger reflex vergence eye movements (Hands & Read, 2017). Some monocular cues are caused by the spherical shape of the eye, while others are an effect of the spatial array and lighting (Palmer, 2002, p. 229ff.).

- central perspective: the convergence of lines in the centre of the optical horizon, caused by the spherical form of the eyes.
- relative size: objects that are further away are smaller
- texture gradients: textures get more dense in the distance
- occlusion: objects in the front occlude objects in the back, but not vice versa
- aerial perspective: objects in the distance tend to look paler due to atmospheric overlap
- shadow cues: shadows indicate the three dimensional form and position of an object

3.2.3. Perception of self-movement

Gibson’s Ecological theory of perception stresses the importance of self-movement for vision, and integrates monocular cues and other factors of spatial environment perception, such as objects size, texture gradients, horizons, and foregrounds/background etc. into a unified model (Gibson J. J., 1986). According to his model, the pattern of light that reaches the eye can be thought of as an optic array that provides information about the layout of objects in space. The optic array is in a state of constant optic flow through self-movement, as the observer looks towards a focal point on the optic horizon. The optic horizon is identical to the relative height of the eyes.

The optic array consists of objects hierarchically organised by distance and diminishing size, forming angles relative to the focal point and to each other. During self-movement, these scales and angles, and the object’s texture gradients change, providing information about the direction, distance and speed of the observer in relation to the environment.



Optic flow of a plane approaching an airfield (source*:* J. J. Gibson, 1950), 360° vision and optical horizon (source: Grau 2003).

3.3. Simulation

Simulation in media and arts describes the compensatory generation of missing or incomplete information. In painting, 3D cues are simulated on a 2D surface; in film, editing simulates movement over the course of time, or sound simulates haptic impact; in computer games, mouse movements simulate full body movements of the avatar, and so on. Media can also simulate “invisible” or more abstract content: music can simulate affect (“exciting music”) and lighting can simulate valences such as danger (“It’s dark, don’t go there.”). Simulation usually relies on mechanisms of completion, be they sensory, neural or cognitive.

While more abstract media such as text or music work mainly with simulation, “literal” media such as film use simulation mostly for missing or “invisible” information. Even VR, despite being the “most literal” audiovisual medium, can simulate missing information, affect or valences.

3.3.1. “Filling in”

Slater and colleagues discuss the importance of sensory completion for simulation in VR (Slater, Lotto, Arnold, & Sanchez-Vives, 2009). They state that all perception is multi-modal and includes learned correlations that “fill in” missing data, for example when a user touches something red in a VR environment, she may report feeling heat. Correlations are linked by similarities in modality, intensity, location, and duration.

Multimodality happens on a neuronal level. For example vision includes the activation of somatosensory, motor and emotion-related brain networks. At the same time, motor neurons respond to visual, tactile and auditory stimuli (Gallese, 2014).

Another type of simulation is based on sensorimotor prediction, due to the incompleteness of sensory data. For example, a visual signal needs about 1/10 sec. to reach the brain. During fast movements, when the signal reaches the brain, the spatial situation may have already changed significantly. Despite this, we are able to catch a ball that moves faster, and we believe that we see the ball approaching, even though the visual data is not there yet. Changizi and colleagues have shown that to be able to perceive the present situation, the brain pre-calculates movements by combining specific visual cues, such as motion blur, optic flow and change of angles, with proprioceptive information about self-movement, creating optical simulations or illusions (Changizi, Hsieh, Nijhawanc, & Kanaib, 2008) (Changizi M. , 2010, p. 73) (Wexler & Klam, 2010). Visual illusions can be even caused by muscle stimulation when optic information is restricted (DiZio & et.al., 2015).

3.3.2. Action activation and neural “mirroring”

The so-called mirror neuron system has the capacity to integrate visual, auditory and motor systems. Mirror neurons have been called “audiovisual” neurons with the “ability to code abstract contents – the meaning of actions.” (Kohler, Keysers, Umiltà, Fogassi, Gallese, & G., 2002). By their integration of the motor system and the sensory system, mirror neurons integrate action and reaction, leading to a constant stream of experiential meaning-making that has been connected to the sensorimotor loop (Hanuschkin, Ganguli, & Hahnloser, 2013).

While filling-in simulates missing sensory cues through a process of completion, the perception of movements, objects, or layouts can also cause a “filling-in” of neuronal action activation through an action execution–perception link within the mirror neuron system. Gallese and colleagues observe that specific motor areas in the brains of monkeys are not only activated when the monkey executes an action, but that the same neurons fire when the monkey observes someone else executing the action. These findings have been interpreted as a mirror neuron pattern of parallel motor cortex activation, both during action execution and action observation. Neural motor activation is also observed in humans when they perceive still photos of people in motion (Kourtzi & Kanwisher, 2000). Likewise, audiovisual media activate multimodal reaction through simultaneous multi-sensory cues. Multimodality can be viewed as the basis of affect and empathy during media consumption . (Heimann, Umiltà, Guerra, & Gallese, 2014) (Ghazanfar & Schroeder, 2006) (Gallese, Keysers, & Rizzolatti, 2004) (Shimojo & Shams, 2001).

Further studies have shown that neural action activations not only happen when observing others, but that a large number of sensory inputs can trigger them. According to Gallese, mirror mechanisms relate to the perception and interpretation of space, interactions and objects, i.e. objects in space are classified by the brain as potential targets of different types of interaction (Gallese, 2014). This might be seen as support of Gibson's earlier model that objects and environments carry *affordances*, or perceived action possibilities (Gibson J. J., 1986).

Referring to Gallese's work, Ward states that: "embodied simulation is a neural mechanism for coding space in egocentric terms. Peripersonal space is anchored to specific parts of the body to create a 'motor space' within which a repertoire of potential motor schemas may be simulated and executed. The function of motor space is to map affordances and relationships between objects and actions." (Ward, 2015, p. 169). Studies in monkeys have shown specialised premotor neuronal activation, depending on the distance between the perceiver and the sensory input, specifically the difference between peripersonal space and extrapersonal space (Heimann, Umiltà, Guerra, & Gallese, 2014) (Gallese, 2014).

And Gregersen and Grodal argue that controller interaction in computer games activates the motor system/mirror neuron system through the observation of and interaction with avatars and environmental factors (Gregerson & Grodal, 2009).

3.3.3. Cognitive mapping

Kathrin Fahlenbrach adapts the cognitive model of *image schemas* to analyse environments in film and computer games and to understand how perceptual meaning and valence are spatially simulated and mapped (Fahlenbrach K. , 2010) (Fahlenbrach K. , Embodied spaces: film spaces as (leading) audiovisual metaphors, 2007). Tim Rohrer describes image schemas as dynamic activation patterns that are connected to neural simulation, and shared across the neural maps of the sensorimotor cortex (Rohrer, 2005).

The concept of image schemas is based on the empirical research of Leonard Talmy and Ronald W. Langacker; across unrelated languages, they first observe underlying, universal primitive schemas for paths, bounded regions, contact and forces, often in combination with conceptual meanings (Hampe, 2005) (Kövesces, 2010).

Due to their conceptual nature, image schemas can not only manifest in languages, but in non-linguistic sign systems as well. Image schemas have been observed in a high number of non-linguistic sign systems, such as comics, sign languages and dance, and even sound design (Kövesces, 2010) (Hampe, 2005). For film, games: (Fahlenbrach K. , 2016) (Fahlenbrach K. , Embodied spaces: film spaces as (leading) audiovisual metaphors, 2007); cartoon: (Forceville & Urios-Aparisi, 2009); music and sound design: (Coëgnarts & Kravanja, 2015).

Mark Johnson proposes that image schemas are recurrent patterns of human perception, action and conception that arise from sensorimotor interaction with a physical environment (Johnson, 1987).

Image schemas refer to fundamental structures such as:

Body-related	Movement-related	Object-related	Force-related
Right-Left, Right-Left Symmetry	Verticality, Up-Down	Container	Compulsion
Front-Back	Rectilinear movement	Part-Whole	Attraction
Near-Far	Curves	Merging/Splitting	Blockage
Horizon (Eye)	Source-Path-Goal	Full-Empty	Speed, Rhythm
Centre-Periphery (including Focal Area)	Balance	Mass/Count	Scalarity, Intensity

Exemplary orientational image schemas (source: Johnson 1987:126).

Image schemas

- are recurring across diverse bodily experiences
- are image-like in that they preserve the topological structure of the complete perceptual experience
- link sensorimotor experience to conceptualisation
- are probably instantiated as activation patterns in topologic and topographic maps
- contain a relatively small number of components
- and have an internal pattern-completion structure that serves as the basis for inferences

(Johnson, The Body in the Mind: The Bodily Basis Of Meaning, 1987, p. 29) (Rohrer, 2005, p. 173).

For example the image schema SOURCE-PATH-GOAL

- is based on everyday recurring experiences of self-motion that date back to early childhood.
- contains the components: *Mover, Source, Path, Goal.*
- allows inferences such as: if you are at the goal location you have already been at the source and path locations, etc. (Dodge & Lakoff, 2005, S. 58ff.).

Image schemas have been defined as classes or recurring patterns of sensory-motor experiences and as perceiver-environment interactions that have meaning (Johnson, 2005, p. 16ff.). As part of what George Lakoff and Mark Johnson call the “cognitive unconscious”, they are essential carriers of spatial logic, and play a central role in the discrimination of our bodily orientation and experience (Johnson, 2005, p. 22). Through their embedded inferences they also form primitive building blocks for logical and abstract reasoning, including mathematics (Lakoff & Nunez, 2000, p. 5ff.).

Image schemas are also the building blocks for conceptual mappings and metaphors. According to Lakoff, cognitive processes are “largely metaphorical, making use of the same sensory-motor system that runs the body.” (Lakoff G. , 2003, p. 3). That means, “metaphor” is here not defined in the poetic sense, but as a cognitive tool that allows the reuse physiological experiences for completion, inference, valence, and affect mappings.

These metaphorical mappings are systematic and non-arbitrary. They arise from physical correlations, similarities and primitive associations, for example:

- Red = Heat (the colour of substances changes with temperature) → COLOUR maps TEMPERATURE
- Dark = Bad (orientation is difficult in the dark, which can be the cause of accidents) → LIGHT maps VALENCE/AFFECT
- Up = More (the level rises when substances are added, one can see more from a high position) → HEIGHT maps QUALITY/POWER/CONTROL

Metonyms are a subtype of metaphor. In visual media, target domains are often elicited metonymically, that is: the mapping happens within one single conceptual domain rather than across two distinctive domains. For example one part of the domain stands for the whole domain and vice versa, or the cause stands for the effect, and vice versa: The colour red or red light (EFFECT) is used to simulate heat (CAUSE); or silence (EFFECT) is used to simulate the numbness of shock (CAUSE). Metonymical mapping seems to be the basis of Ward’s “reverse engineering” by “hacking into” processes of neuronal and sensory filling-in, so that touching a red object in VR can actually elicit haptic sensations of heat (see above).

While culture plays a central role in the way these mappings are expressed, a number of underlying structures seem to be universal and connected to the physiological experience of having a human body in a physical, gravitational environment. This can even influence valence mappings.

For example: RIGHT-LEFT is used in the spatial metaphor RIGHT IS GOOD - LEFT IS BAD. In a series of empirical studies Casasanto et al. have shown that these mappings are not primarily culturally determined, but can be found across separate cultures and seem to be connected to individual handedness. Object and creature preference on the side of handedness has been demonstrated in children as young as five years and in adults (Casasanto, 2009) (Casasanto & Henetz, 2012).

These mappings are not static, but bound to body specificity, and are malleable by changes in the body: When handedness is damaged through stroke, or when it is artificially obstructed, the positive/negative mapping reverses (Casasanto & Chrysikou, 2011).

Also, the mapping switches, when a right-handed participant judges the side-valence of another person or fictional character who is left-handed, or when the character has an injury on their right hand (Kominsky & Casasanto, 2013).

3.4. Spatial-temporal structuring

When a new medium is evolving, it usually borrows spatial-temporal structuring techniques from the media that came before it. Early film used the stage set-up and act structure of theatre, early computer games used text or film structures (“Choose your own adventure”, interactive film), and so on. It can take several years or even decades of design experiments and technological development to find structuring techniques that are adequate for the medium.

Current consumer VR borrows techniques from film, mainly for pre-rendered VR and 360° stereo film, and from computer games, for real-time rendered VR.

	Film	**3D Games**	**VR**
Spatial	Set Design / Composition	3D Layout	3D Layout
	Camera movement	Paths	Paths
	Lighting	Lighting	Lighting
Temporal	Editing	Levels / Health / Lives	?
	Camera Movement	Avatar movement	Self-movement
	Action	Interaction / Animation	Interaction / Animation

Spatial design elements such as general layout, environment animation, light and sound design, that direct attention and structure space and time, are functional in all audio-visual media, including VR.

But interactive media, including many computer games and real-time rendered VR, hand over movement and camera control to the user, which strongly limits the designer's control over what the user sees at any given place or time.

A lack of camera control means that a film-like editing is not possible. Temporal structuring and "rhythm" in computer games is achieved instead through motion design, i.e. the design of shape and speed of movements, such as walking, running, and jumping, which can be assembled into longer "cascades" of movement. But in VR, the motion sickness that results from animated movement in conflict with self-movement restricts animated movement as a structuring tool.

Additional structuring in computer games is usually achieved by extra-diegetic or UI elements, including level structure, maps, health and life bars, and so on. But in VR, as soon as place illusion is established, there is not extra-diegetic UI space, phenomenologically speaking. Everything is part of the spatial experience. For that reason, extra-diegetic, abstract elements such as floating text and numbers are known to break immersion in VR, if they are not carefully integrated into the environment as "physical", non-abstract objects.

A physically immersive, but narratively extra-diegetic "waiting room" that integrates UI elements, such as buttons in the form of floating images, seems to be functional in VR. But a typical computer game flow of switching between in-game environments and UI areas would mean a constant teleportation between different "physical" places or "levels of reality" in VR, which can be disorienting and also induce motion sickness.

As has been discussed before, VR applications belong to the group of spatially immersive systems such as panoramas or theme parks. For that reason, environmental design for VR has a lot in common with traditional garden or theme park design (Younger, 2016) (Lamm, 2002).

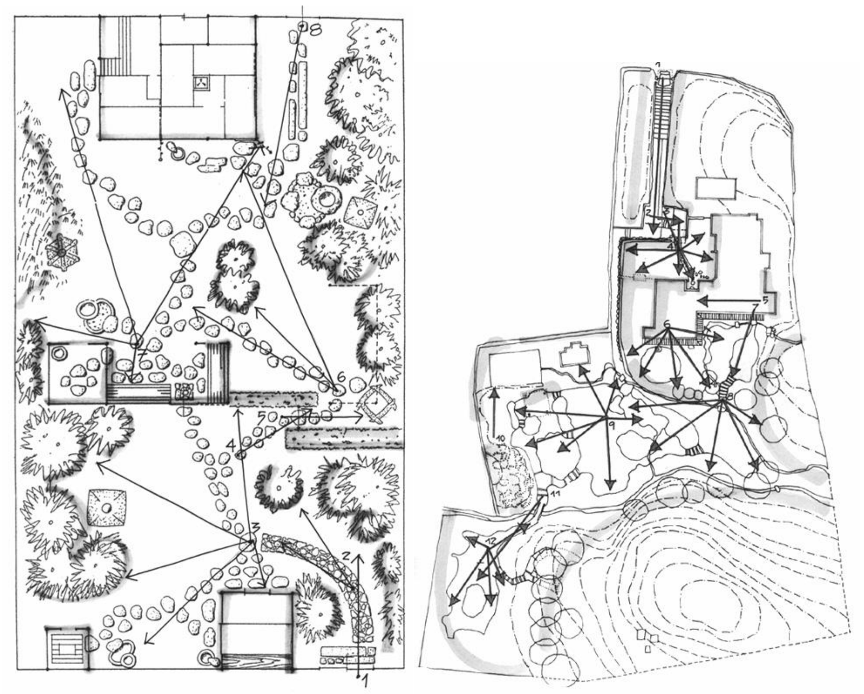
There, time is structured by entry and exit times ("We need to see these 10 attraction before the park closes"), and the self-movement between these points is mainly organised by spatial means such as paths and obstacles.

While 2D media with camera control allow the composition of "shots" or "tableaus" on a flat viewing plane, compositing a 360° spherical view is more complex. The problem is exacerbated by self-movement, which means that all established relations and angles of the compositional array will shift due to motion parallax. Any given area of the environment will look completely different, depending on the changing position of the viewer.

Traditional garden design, for example English landscape garden design of the 18th century, has managed that problem by restricting vision and access through obstacles, and by establishing lines of view or vistas at specific significant points in space.

The spatial layout organizes experience in time by the order of important vistas, which are connected by paths. Analysing traditional Japanese garden design, Despina Sfakiotaki has called this the design of "movement in sequential space" (Sfakiotaki, 2005).

Additional temporal structuring can be provided by intradiegetic events such as sounds, animations and interactions that are triggered at specific points in space and time.



Two Japanese garden designs with paths, vistas and obstacles (source: Sfakiotaki 2005).

3.5. Sensorimotor affordances

[Disney Imagineer Tony Baxter about Walt Disney's Haunted Mansion attraction:] *"While backgrounds support the animation in film, the backgrounds are what the rides are all about. You are the animation going through the ride, and the ride is the background come to life."* (Baham, 2014, p. 49).

So far I have shown in what way the sensorimotor functions of the body, mediated through VR technology, generate information about the self, the environment and self-movement, and how this information can form the basis for simulation and spatial-temporal structuring.
In this part I analyse the basic parameters of VR environments to understand how they function as sensorimotor affordances for information, simulation and spatial-temporal structuring.

The following types of environmental parameters are related to self-perception, environment perception, movement perception and additional information:

	PARAMETERS
Self-perception	Translation/position
	Rotation
	Scale
Environment perception	Layout
	Surface/material
	Lighting
Movement perception	Self-movement
	Animation (environment)
	Interaction
Other (optional)	Sound
	Haptics
	Chemical

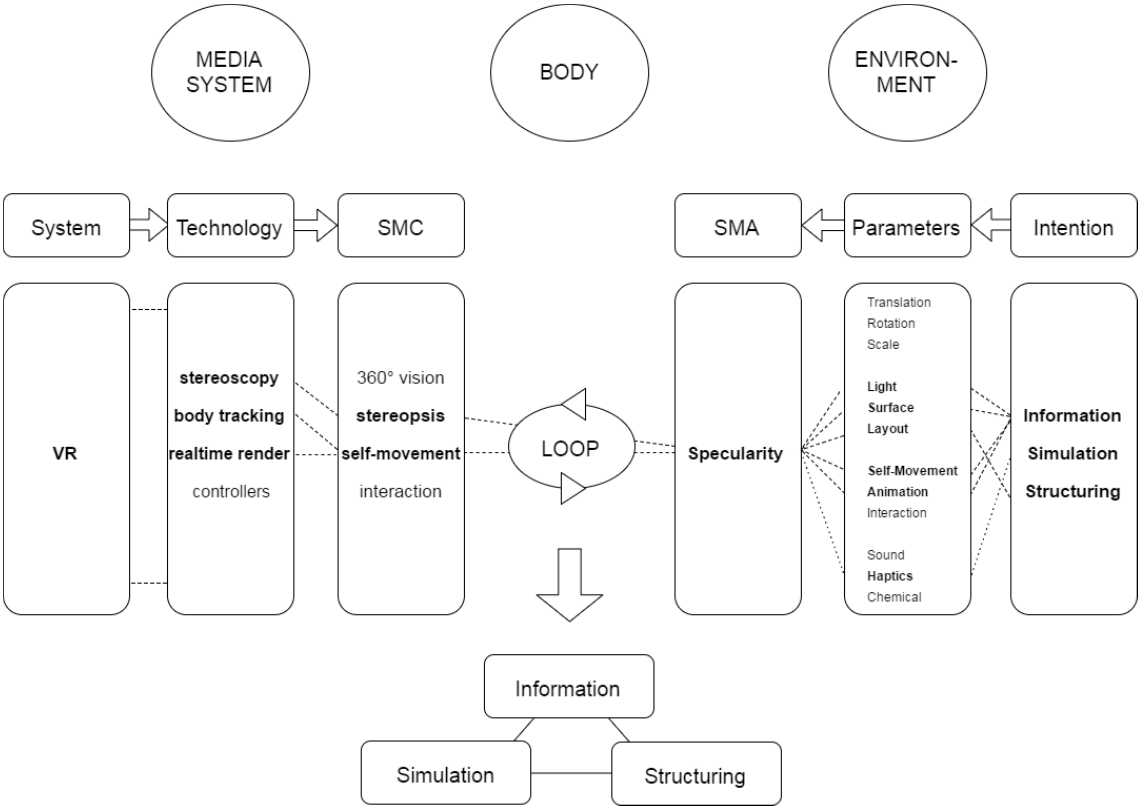
Environmental affordances can be classified by parameter type, for example specularity can be classified as a surface parameter. With a general understanding of how surfaces function as sensorimotor affordances in VR, a designer can make predictions about specific surface affordances, such as specularity, colour, micro detail and so on, and utilize them within the environment.

An affordance such as specularity can be used for a high number of design intentions, i.e. for information, simulation and spatial-temporal structuring. Surface specularity is perceived through vision, in combination with self-movement. When the user moves, the highlights on the surface move with her. That way, specularity provides information about the user's changing position in space, about movement speed, rotation and direction. Similar information is provided for animated objects.

Specularity also generates information about several environmental parameters, for example about the changing light situation and an object's general surface qualities such as roughness, wetness and age.

Through filling-in, specularity simulates an object's materiality, including hapticity, weight, and so on. This information and simulation can lead to action activation. Specularity can also map age and backstory, valence and affect, for example through shininess/dirtiness.

And specularity can function as a spatial-temporal structuring tool to direct attention, movement and interaction within the layout.



Unified model integrating the sensorimotor loop with perceptual design, example: specularity (source: author).

3.5.1. Sensorimotor affordances: position, rotation, scale

SMC	SMA	INFORMATION	SIMULATION	MAPPING	STRUCTURING
Vision, audio, proprioception	Position (x,y,z)	**Self-Position**	Action activation	LEFT-RIGHT, UP-DOWN, FRONT-BACK	Spatial, temporal
Vestibular, proprioception, 360° vision, audio	Verticals, ground, layout	**Self-Rotation**	In/stability	BALANCE, VALENCE	Spatial
Eye position proprioception	Environment scale	**Self-Scale**	Control	BIG-SMALL, UP-DOWN VALENCE	Spatial

Information

Self-perception is the background on which environment perception happens. Even in a completely dark and silent environment, we are usually aware of the rotation and posture of our body in relation to gravity, by way of the vestibular sense, proprioception and haptics.

To perceive the relative position and scale of our body in space, we need only a few environmental affordances: Even though the virtual "White Room" of the HTC Vive, which is visible during loading operations, is just a spherical grid on a white background, it creates immediate place illusion.

From the grid, users know their relative x,y and z coordinates within the environment, their rotation around the y axis (gaze direction), the x and z axes (tilt) in relation to the environment, and their scale relative to the environment.

The "white room" places users in the middle of the grid, but they could be placed at any position within that environment, for example 10 metres in the air, upside down, with a tilt of 30°, and the size of an ant. Clearly, relative position, rotation and scale in space strongly influence how the user perceives the environment.

Information about position and scale are mainly gathered by visual means, i.e. eye position, eye distance and eye height, relative to the environment, and are therefore fully provided by the HMD. But rotation around the x and z axes (tilt) is also perceived through the vestibular sense, relative to physical gravity, and can be in possible conflict with visual information about tilt within the VR environment.

As we have seen, the vestibular sense can adapt to visual cues from the environment, such as strong vertical cues. i.e. if the VR environment is titled, the resulting sensory conflict and visual capture can cause loss of balance in the user.

Simulation

Position, rotation and scale are also strongly associated with orientational image schemas such as FRONT-BACK, LEFT-RIGHT, UP-DOWN, BIG-SMALL, and the VERTICALITY and BALANCE schema, and can be used to map a high number of concepts, valences and meanings.

Valence is mapped to left and right environment areas according to handedness, possibly with corresponding action activation. Tilt maps balance and stability, which in turn maps valence and control. Valences such as power and control are also mapped by relative height and size: looking up to something will be experienced differently than looking down on something.

Spatial-temporal structuring

Visual attention is naturally directed to the front of the user, while environment areas in the back are invisible until she turns around the y axis. But sound may be heard from all directions. Areas of peripheral vision in all four directions can be activated by drawing attention to them with environmental affordances.

The high number of environmental parameters that are affected by user position explain the central importance of establishing 360° vistas in VR environments, for example as starting positions or at certain points of heightened interest within the simulation. These carefully chosen positions are a central spatial-temporal structuring technique of VR.

3.5.2. Sensorimotor affordances: layout

SMC	SMA	INFORMATION	SIMULATION	MAPPING	STRUCTURING
Monocular cues, stereoscopy, self-movement	Position xyz, layering, obstruction, foreground middle ground background, scale	**Layout**	Completion, action activation, self-movement	LEFT-RIGHT, UP-DOWN, FRONT-BACK, BIG-SMALL, NEAR-FAR, BALANCE, CONTAINER	Spatial, temporal

Information

In general, an environment layout is perceived through monocular and stereoscopic cues that can be amplified by self-movement. The visible environment consists of objects situated at x,y and z positions in space that form the basis for the optic array, i.e. the layout of the environment in space is perceived as a pattern of layers, occlusions and angles. They are the affordances for depth perception and spatial mapping, such as distance perception, scale perception, or layout perception.

Distance can be roughly subdivided into foreground, middle ground and background, depending on the following affordances: Relative object size gradually decreases from foreground to background, while parallel lines converge. Objects in the front will occlude objects in the back and colours get paler as they are occluded by the atmosphere.

The patterns of the optic array form the building blocks for designing a 360° vista.

As a VR environment may be perceived from several vistas over the course of time, it has to be built with *multiperspection* in mind. The layout needs to be spatially meaningful, not just from one position, direction, distance or height, but from several.

Landscape and especially theme park design have developed a high number of techniques to organize complex spatial layouts of environments and increase multiperspection, for example through *stratification*, or the layering of objects and masses in x and z space, *multilevelling*, or the building of environments at different heights along the y axis, and *interweaving* and *"borrowing landscapes"*, or the spatial integration and overlap of different foreground and background areas (Younger, 2016) (Sfakiotaki, 2005).

Simulation and mapping

In both theme parks and computer games, stratification and layering are used to create illusions of endless or "implied" space, and to save resources (Younger, 2016, p. 168ff.). As the environment in the "real world" is always "endless", the user will mentally fill in implied, but non-existent distant areas.

While the management of restricted space and resources is not as important for virtual environments as for physical environments, even open-world computer games have boundaries, and these boundaries need to be hidden in some way.

2D and 2.5D techniques may be used for budget reasons, but as in real life, they only work from a restricted point of view, for example through a window. Partly obstructed areas are mentally "filled in", i.e. the environment does not have to be completed in all areas (Younger, 2016). Filling-in is also triggered by the use of false portals, such as doors, staircases, hatches, or ladders that lead nowhere, and by "peaking", i.e. by showing protruding parts such as towers or masts that "peek" over other areas and indicate (non-existent) complete buildings or ships behind the obstacle (Younger, 2016).

Other spatial simulation techniques such as forced perspective are less important for virtual 3D environments. But Trompe-l'oeil is often used for background elements such as sky boxes, which are, technically speaking, matte paintings.

Multiperspection in a theme park environment (source: Walt Disney Star Wars)

Multilevelling, Stratification (source: Franklin Chan, Art Station , *Tom Clancy’s The Division*, 2016).

DOWN and UP schemas in *Spec Ops - The Line* (2012) and *Journey* (2012).

Depending on their distance, objects or environment elements cause different reactions. Objects and elements in the foreground and near middle ground, such as tools, doors, abysses or paths, suggest the possibility of movement and interaction, and can trigger action activation.

Environment rotation can simulate movement, and even a slightly tilted environment can affect balance and suggest instability.

The combined use of position and scale can trigger powerful physical reactions, and might be one of the most important design techniques for VR environment; for example a narrow tunnel, a wide open landscape, a high cliff or a low ceiling can induce affects and reactions such as claustrophobia, vertigo, and different types of action activations.

Layout also plays a major role for cognitive mapping through orientational image schemas, such as UP-DOWN, NEAR-FAR, BIG-SMALL, or the BALANCE, SOURCE-PATH-GOAL and CONTAINER schemas.

An example: The simple valence mapping Up = good / down = bad is used in numerous computer games. Through ever-descending spaces, *Spec Ops: The Line* (Yaeger Development, 2012) builds the gradually decreasing mental stability and loss of control of the protagonist into the environment. The poetic *Journey* (thatgamecompany, 2012) embodies the metaphysical ascent of the protagonists as a physical ascent to a mountain top.

Fahlenbrach discusses the spatial design of the computer game *Arkham Asylum* (Eidos Interactive, 2011), where the main building, a lunatic asylum in an old castle on an island, provides a sensorimotor experience of the madness of the game’s antagonist, the Joker. Referring to the CONTAINER schema and INSIDE/OUTSIDE image schemas, the building spatialises conceptual metaphors such as

- Madness is a closed building
- Madness is a maze
- Madness is isolation

Accordingly, the building conveys sensations of being trapped, of disorientation and psychotic opaqueness. The aggressive, manic and dark mood is further enhanced by the set design, colour grading and lighting. Madness is also embodied through sound design such as the distant voices in corridors:

- Madness is hearing voices

The building functions as an arena for the game’s hunter/prey ludic structure that is dominated by a pervasive dichotomy of good-versus-evil, through the recurring spatial mapping of:

UP / DOWN =

- good / bad
- sane / insane
- rational / irrational

This dichotomy is reinforced by the possible positions of the avatars within the environment. While the antagonists are mainly relegated to the ground, Batman can fly and jump to higher vantage points, providing him with god-like detachment, (self-) control and overview (Fahlenbrach K. , 2016).

Spatial-temporal structuring

Both theme parks and computer game environments with first person perspective are organized in space and time as a string of vistas along a path, or a network of paths. By controlling the layout, the designer directs the attention of the user. Differences in height, shape or material function as landmarks that draw the eye, while obstacles obstruct vision and distract attention. That way, the layout can provide both orientation and disorientation; it can disguise and gradually reveal areas.

Layering and obstruction are simple, but powerful tools to structure and control spatial perception and self-movement in VR. In combination with position, they are the closest VR design gets to composition and editing. For example, when obstacles such as walls or rocks provide windows to areas of the environment that cannot (yet) be accessed, this is a form of temporal foreshadowing, or *windowing* (Younger, 2016).

Obstruction is closely related to multiperspection as a temporal structuring tool, as the different vantage points need to be experienced over time, encouraging the user to actively explore the environment and “piece together space in their mind” (Younger 2016:1975). When first walking under a bridge and then later over the bridge, or when first being on one side of a river and then on the other, the user begins to understand her own former position in space and the layout as a whole. These spatial-temporal sequences can be used to build up dramaturgic effect.

Access restriction in space or time indirectly relies on filling-in, in that it makes the user aware that she does not know everything about the situation. This can also increase the suspension of disbelief (Younger 2016:191).

Environments for computer games contain some of the most advanced examples of environmental storytelling, i.e. sequential exploration of meaning through environment. That way they can even communicate temporal factors such as backstory or future goals.

An environment can spatialize not only the temporal order of events, the story’s progress and rhythm, but also ludic structure, rules and goals, for example in *Arkham Asylum*:

1. Entering a place ruled by madness
2. Orientating within the place and finding the source of the madness
3. Defeating the madness / Freeing the building.

3.5.3. Sensorimotor affordances: surface and light

SMC	SMA	INFORMATION	SIMULATION	MAPPING	STRUCTURING
Self-movement, stereoscopy	Specularity/ roughness, microdetail, resolution, occlusion	**Surface**	Material properties, weight, haptics, age	ROUGH-SMOOTH, LIGHT-HEAVY, VALENCE	Spatial
Vision	Intensity, direction, colour, shadow	**Light**	Temperature, atmosphere	LIGHT-DARK, HOT-COLD, VALENCE	Spatial

Information

The distinction between objects and surfaces is somewhat random. Are the pebbles that cover a seaside objects or surface properties? Where does object scale end and surface scale begin? Like objects, the details on a surface can have overlap and occlude during motion parallax.

Wherever one draws the line, surfaces provide strong affordances for distance and scale perception through monocular cues, such as texture and shadow gradients, and occlusion. They also provide feedback about self-movement, object movement and speed.

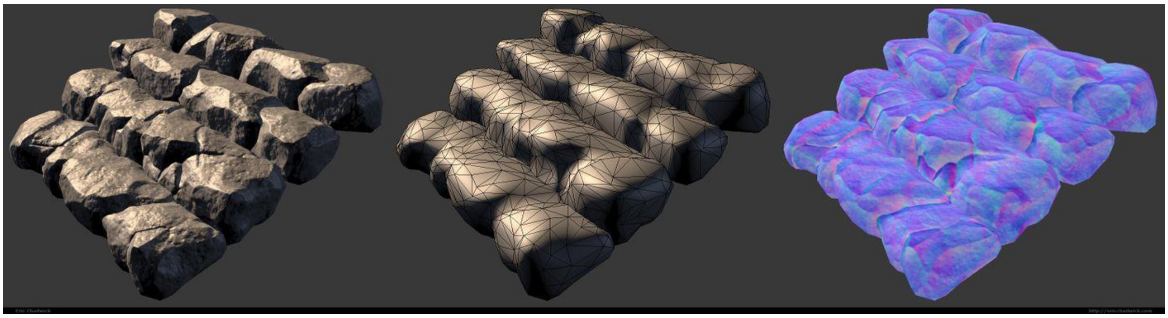
The material properties of an object are mainly perceived as surface properties such as roughness, specularity (glossiness), reflectivity, transparency, colour and so on.

The perception of these properties is always influenced by the light situation, sometimes strongly so: Light colour can shift surface colour to a completely different tone.

Light perception generates information about light direction and intensity. But light also shades form, while drop shadow clarifies position, turning both into strong affordances for spatial perception.

Surface properties play a central role in questions of “realism” and style. The amount of surface detail and the degree of realism of surface properties such as reflectivity seems to determine how “real” an environment is perceived: stylisation, for example in cartoons, is mainly a reduction and simplification of surface detail and surface properties.

As Khanna et al. note, “realism” in not one thing, but can be separated into different categories such as geometry realism, surface realism, lighting realism and so on. These factors function separately from each other, for example even a highly stylized environment without surface detail can have a high degree of lighting realism (Khanna, Yu, Mortensen, & Slater, 2006).



Detail gradient with normal map, specularity, shadow and occlusion (source: Polycount Wiki)

Full set of PBR maps and a surface with complete PBR material (source: Allegorithmic, Substance Share).

Environment realism versus avatar stylisation (source: *Dishonored 2, 2016*).

Guiding attention though light and colour (source: *Alan Wake*, 2010; *The Last of Us* 2013)

By experience, game designer have long known what an ECG and survey based study by Vinayagamoorthy,and colleagues confirms for VR: Higher realism and high texture detail in environments increases presence. But characters (NPC) with high visual realism decrease presence when they are more realistically textured, probably due to a mild uncanny valley effect (Vinayagamoorthy, Brogni, Gillies, Slater, & Steed, 2004).

The lowest presence is caused by a combination of more realistic characters with less realistic, tiled-texture environments. A combination of a more realistic environment with stylised NPCs causes the most consistent presence, while a combination of less realistic environment and stylised characters is equally well accepted. Not surprisingly, computer game artists show a preference for either consistently stylised game content, or for combinations of more realistic environments with more stylised characters (but rarely vice versa).

Simulation

Strictly speaking, colour maps with baked-in spatial detail and light can be described as trompe-l'oeil, i.e. they simulate form in space on a flat surface. Depending on the distance, self-motion might break this simulation, due to a lack of occlusion and real-time specularity and shadow. Specific types of maps such as normal maps or parallax occlusion maps simulate real-time spatial lighting, shadow and occlusion, and so work as sensorimotor affordances that react to self-movement. Specularity, roughness and metalness maps equally function as movement affordances by simulating reflectivity. Some of these maps, normal maps in particular, were developed for monocular (screen) view and function only partially in VR, as they lack information for a second eye position.

Surface colour and lighting in VR can cause "filling-in" of haptic sensation: When touching a red area in VR, users felt haptic warmth (Slater, Lotto, Arnold, & Sanchez-Vives, 2009). Possibly this haptic "filling-in" also works with other visual surface information such as roughness, smoothness, and so on (if it is not contradicted by physical haptic input, see below).

Surface information might also influence action activation, in that it communicates if an action is viable, for example if a path through a swamp is safe to walk on, if an object is too heavy to lift, and so on.

Generally speaking, surfaces map valence and safety/danger through their haptic qualities, such as fluffy, edged/sharp or red-hot.

Surface colours and patterns can map meaning, for example when the meandering pattern of the carpet in *The Shining* (1980) foreshadows the dangerous labyrinth in the garden of the hotel.

As lighting is a strong indicator for temperature, it is connected to the mapping of atmosphere, for example through weather cues and aggregate states.

Linguistic studies have shown that aggregate states are globally used to map mood, affect and emotion, for example through EMOTION IS LIQUID metaphors, such as ANGER IS HOT/ A HOT FLUID IN A CONTAINER (Fahlenbrach K. , 2010, p. 218) (Kövesces, 2010).

Within a VR environment these mappings can be spatially experienced, for example when walking through a thunderstorm during an emotionally upsetting sequence, or when the eruption of a volcano maps the anger and destructive energy of an antagonist.

Spatial-temporal structuring

In VR, guiding the attention of a user within a 360° environment is often difficult, but differences in surface cues, for example the different surface properties of a path in contrast to the surrounding grass, guide object recognition and attention. Other strong cues for spatial direction are lighting and colour. They are not just used to draw attention but also to hide areas or objects, and create “negative” or “invisible” space (Younger, 2016).

Surface ageing can be seen as a form of temporal structuring that can communicate backstory or change over time.

3.5.4. Sensorimotor affordances: Self-movement, animation, interaction

SMC	SMA	INFORMATION	SIMULATION	MAPPING	STRUCTURING
Optic flow	speed, type, direction	**Self-movement**	Progress	SOURCE-PATH-GOAL	Temporal, spatial
Optic array	speed, type, direction	**Animation (Env.)**	Self-movement	BALANCE, VALENCE	Temporal
Self-movement, hand interaction	Type	**Interaction**	Haptics. force	FORCE	Temporal

Information

As discussed before, self-movement is a central sensorimotor contingency for perception.

It amplifies spatial perception through motion parallax, both visually and aurally. Visual motion parallax is defined as the change or optic flow of angles, occlusions and scales in the optic array during self-movement. These changes follow specific rules, depending on distance, i.e. the closer the objects, the stronger the changes. It follows that surface properties are significant affordances for self-movement when seen at close range. Object layering, and by extension surface detail, increases the number of angles, occlusion and scale gradients, which provide strong affordances for self-movement, and seem to increase presence (Hvass, Larsen, Vendelbo, Nilsson, Nordahl, & Serafin, 2017) (Toczek, 2016).

Other environmental affordances for self-movement are the way light reflections move in relation to the observer’s position, and the moving shadow of the observer. Both have been shown to increase immersion in VR (Yu, Mortensen, Khanna, & Slater, 2012).

As these properties change during self-movement, they create a sensorimotor feedback loop that provides information about **user position**, **movement**, **speed**, and so on.

When talking about user movement in VR, it is important to distinguish between actual self-movement through tracking, and simulated self-movement through environment animation.

While the former increases immersion through the use of sensorimotor contingencies, animated movement usually conflicts with proprioception and the vestibular sense of acceleration and rotation. For that reason, it can decrease immersion, and is a strong indicator for motion sickness.

On the other hand, animation of objects and areas of the environment, be they avatars, or surfaces such as water or the sky, provide sensorimotor affordances that generate spatial information. Animation, especially in congruent reaction to interaction, seems to increase immersion (Slater, 2009).

Simulation

Computer games work heavily with conceptual abstractions of movement, for example when pointing a cursor on the extradiegetic 2D map of an environment to "jump" to different locations, and reduce travel time. Interactions are abstracted when reduced gestures or controller movements stand in for complete interactions. In VR these abstractions need to be integrated into 3D space, making them diegetic. Well-known examples are teleportation, triggered by 3D "rays", or physical gestures that stand in for more complex interactions.

During these abstracted movements and interactions, the brain seems to fill in missing sensory cues and more nuanced movements, at least to a degree. These simulated movements and interactions, while decreasing realism, can add a layer of "magic" to VR that can increase engagement.

Another case of movement completion, but also of mapping, is the use of the SOURCE-PATH-GOAL schema, which underlies both theme park design and most computer game design.

Seeing a path will immediately trigger inference and completion, as questions about its origin and destination arise. The same holds true for the CONTAINDER schema that comprises all confined spaces such as buildings, rooms, walled cities, fenced in areas and so on, which trigger question about "the other side" behind the separation.

In computer games the SOURCE-PATH-GOAL schema is often mapped as "spatial progress is actual progress", i.e. the spatial progress within an environment is perceived as progress towards more abstract game goals (Fahlenbrach & Schröter, 2016).

In a similar way, the rhythm and type of movement through an environment can map a more general rhythm and valence, for example when physically difficult movement maps emotional difficulty.

To a degree the layout of VR environments can shape self-movement through paths and obstacles, e.g. paths and objects in the foreground can cause action activation and initiate movement, while obstacles can force body distortions such as bowing down, stretching out an arm, and so on.

When obstacles restrict movement, the FORCE schema is activated. It is also important for object interaction, as interactions can be describes as the application of force. In computer games, force-related schemas are closely linked to gameplay patterns, such as:

- compulsion
- blockage
- counterforce
- removal of restraint
- enablement etc.

(Kromhout & Forceville, 2013)

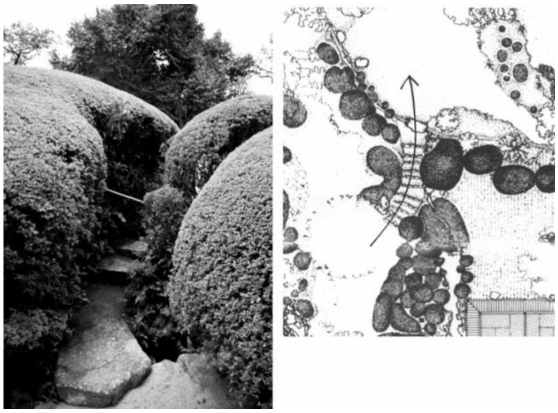
The lack of physical force feedback during interaction can break immersion, so that simulating force feedback, for example through sound, is one of the greatest challenges of VR environment design.

Spatial-temporal structuring

As we have seen self-movement and progress can be controlled through landmarks, obstacles and paths, that spatially and temporally structure an experience. At specific points in time and space users can be encouraged to explore an environment by the promise of new views and discovery moments, through multiperspection and obstruction, or through interactive areas and props.

Environment animations such as scripted events can draw attention and provide dramaturgic “beats” and pacing.

Landmarks and paths (source: *Left for Dead 2*, 2009, *Assassin’s Creed Origins*, 2017)



Movement through obstacles in a Japanese garden (source: Sfakiotaki 2006).

3.5.5. Additional input: sound, haptics, chemical senses

SMC	SMA	INFORMATION	SIMULATION	MAPPING	STRUCTURING
Spatial hearing	Direction, intensity, movement, type	**Sound**	Direction, force feedback, speed, material	-ALL-	Spatial, temporal
Touch, temperature, pain	Surface, force, temperature	**Haptics**	Surface, movement	-ALL-	
Smell, taste		**Chemical**	Visual	VALENCE	

Information

Similar to other audiovisual media, sound in VR is a strong intensifier for immersion and should not be omitted for that reason. Through spatial hearing, sound provides information about the direction, size or movement of objects in space.

Haptic information is usually incomplete or missing in VR. Controllers can provide some haptic feedback, mainly for objects with a similar form, such as tools and weapons. But even if the form or surface material of the controller is similar to the virtual tool, controllers often lack other qualities such as weight or elasticity, and the discrepancy between visual haptic cues and actual haptic cues may cause disconnect.

Controllers usually transfer agency from the user into the environment, but not "patiency" from the environment to the user, i.e. there is no, or only distorted haptic force feedback, which can break immersion (Gregerson & Grodal, 2009, p. 68ff.).

Simulation

Sound can be used to simulate force, weight and other physical feedback in the form of impact sounds.

Some controllers, gloves and suits try to compensate for the lack of haptic feedback with vibration, which can be viewed as an abstraction of force feedback, or a metonymical trigger for filling-in. But vibration has been added with mixed results, depending on the interaction - it might be too subtle or unspecific to simulate heavy impact interactions such as fighting.

Larger VR installations can provide physical feedback such as centrifugal force through moving chairs or other contraptions, or they generate haptic and chemical cues by physical means such as ventilators, smells, and even pieces of string that touch the user's face at specific moments, for example in *The Void.*

Sound and haptics function like sight in that it can map a high number of valences and conceptual metaphor: environmental sounds such as a storm create atmosphere, creature sounds can indicate valence and danger, and touching a slimy material can trigger aversion.

Spatial-temporal structuring

Sound in VR is also a strong spatial-temporal affordance to direct attention, be it through environmental sounds such as impact sounds, or even through voiceover (“look to the right”). That way it can be used to replace abstract UI elements.

Similar to animation, sound can imbue a scene with rhythm and temporal structure.

By providing haptic feedback, large physical VR environments as *The Void* use corridors to structure space and time, as the users feel their way through the environment.

3.6. Sensorimotor framework

SMC	SMA	INFORMATION	SIMULATION	MAPPING	STRUCTURING
Vision, audio, proprioception	Position (x,y,z)	**Self-Position**	Action activation	LEFT-RIGHT, UP-DOWN, FRONT-BACK	Spatial, temporal
Vestibular, proprioception, 360° vision, audio	Verticals, ground, layout	**Self-Rotation**	In/stability	BALANCE, VALENCE	Spatial
Eye position proprioception	Environment scale	**Self-Scale**	Control	BIG-SMALL, UP-DOWN VALENCE	Spatial
Monocular cues, stereoscopy, self-movement	Position xyz, layering, obstruction, foreground middle ground background, scale	**Layout**	Completion, action activation, self-movement	LEFT-RIGHT, UP-DOWN, FRONT-BACK, BIG-SMALL, NEAR-FAR, BALANCE, CONTAINER	Spatial, temporal
Self-movement, stereoscopy	Specularity/ roughness, microdetail, resolution, occlusion	**Surface**	Material properties, weight, haptics, age	ROUGH-SMOOTH, LIGHT-HEAVY, VALENCE	Spatial
Vision	Intensity, direction, colour, shadow	**Light**	Temperature, atmosphere	LIGHT-DARK, HOT-COLD, VALENCE	Spatial
Optic flow	speed, type, direction	**Self-movement**	Progress	SOURCE-PATH-GOAL	Temporal, spatial
Optic array	speed, type, direction	**Animation (Env.)**	Self-movement	BALANCE, VALENCE	Temporal
Self-movement, hand interaction	Type	**Interaction**	Haptics. force	FORCE	Temporal, spatial
Spatial hearing	Direction, intensity, movement, type	**Sound**	Direction, force feedback, speed, material	-ALL-	Spatial, temporal
Touch, temperature, pain	Surface, force, temperature	**Haptics**	Surface, movement	-ALL-	Spatial, temporal
Smell, taste		**Chemical**	Visual	VALENCE	Spatial

4. Implementation

4.1. Wind Turbine

Objective:
Converting the CAD model of a wind turbine into a scientifically accurate VR visualisation for a lay audience at a big public exhibition.

"Experiencing the power of wind turbines."

Hardware and software: Oculus Rift CV, Unity 3D, AQUAS water system, KI Bird Flock, Autodesk Maya

Process:

- Cleaning up and reducing the highly detailed CAD model for real-time rendering
- Modelling a low poly turbine field
- Applying shaders
- Creating a near-photorealistic environment, including a sky sphere and an ocean
- Lighting
- Modifying and adding a flock of seagulls with KI for swarm behaviour
- Modifying and adding an airplane
- Script for distribution of turbine field and animations*
- Script for timing (start, fade in, fade out, animation triggers, sound)*
- Sound design: ocean, wind, rotor, seagulls, airplane
- Voice over with technical information about the wind turbine

*Scripting: Jonathan Becker.

Szenario (~ 3 min. standing/walking experience, 2 x 2 meter)

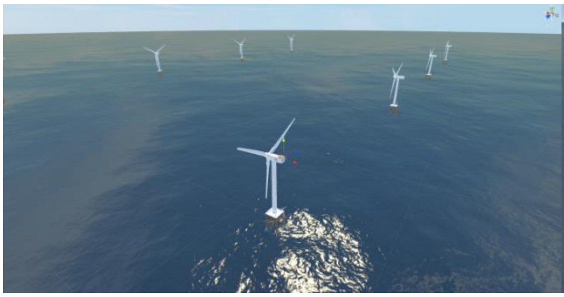
Fade in:

  - Position 1: Lower platform near ladder and crane
  - Voiceover

Fade out.
Fade in

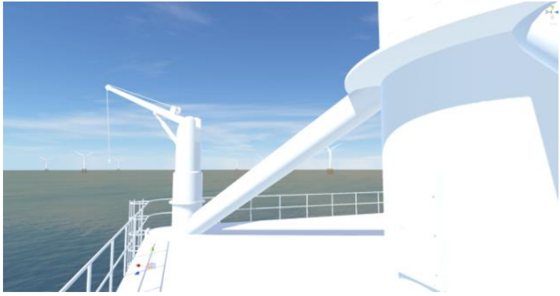
  - Position2: Nacelle (90 m above sea level)
  - Voiceover
  - Animation: Airplane

Fade out



Wind turbine field (25 turbines)

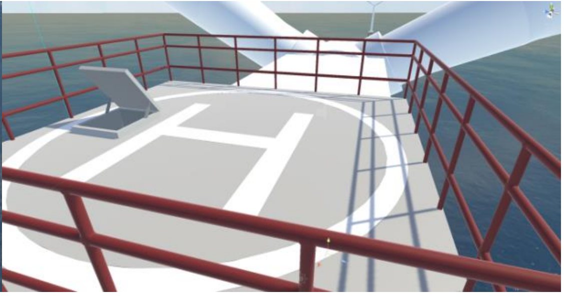
Position1: lower platform



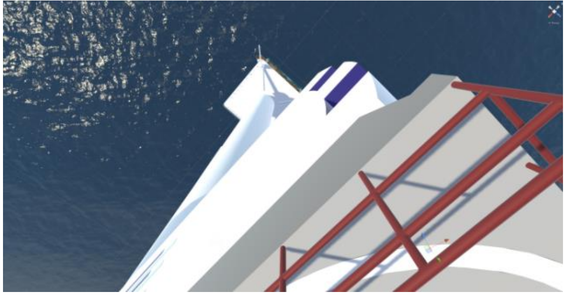
Lower platform: ladder, crane, door

View up from lower platform

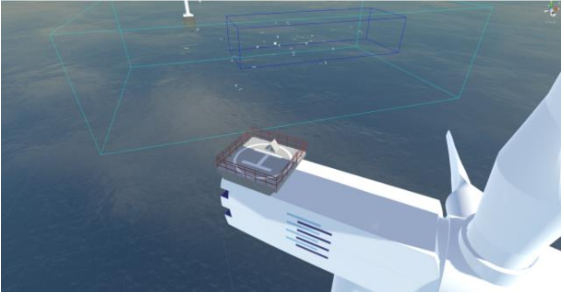
Position 2: upper platform



Upper platform: helicopter cage, rotor, hatch)

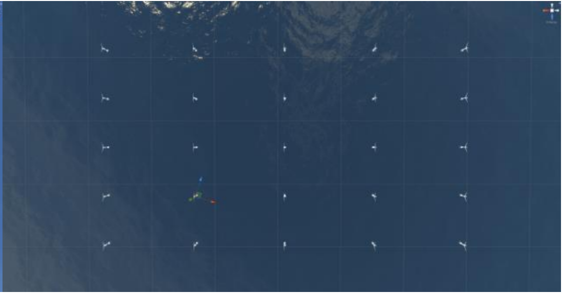


View down from upper platform.



Animated elements: seagulls, real-time shadow

Animated elements: airplane



Top view

Implementation

The objective of the project was to create an experience that allows a mixed audience to experience the power produced by a wind turbine. The customer asked for an Oculus Rift set-up for at least 3 visitors within a restricted area (< 5 x 4 m in total). I decided for a 2 x 2 meter standing experience for 3 users. Preliminary tests showed that the trackers of the Oculus Rift do not conflict with each other, even if they cross in close proximity. The glass walls of the room did not cause tracking problems.

As we expected a massive, mixed-age (5 - 99 years) audience with very different levels of technological experience, I kept the set-up simple and omitted all chances of motion sickness. The experience was scripted to end automatically after about 4 minutes, to keep waiting periods at a minimum.

The experience was also projected on a large screen outside the room so that the audience could simultaneously watch the users inside the glass room and the content of the experience.

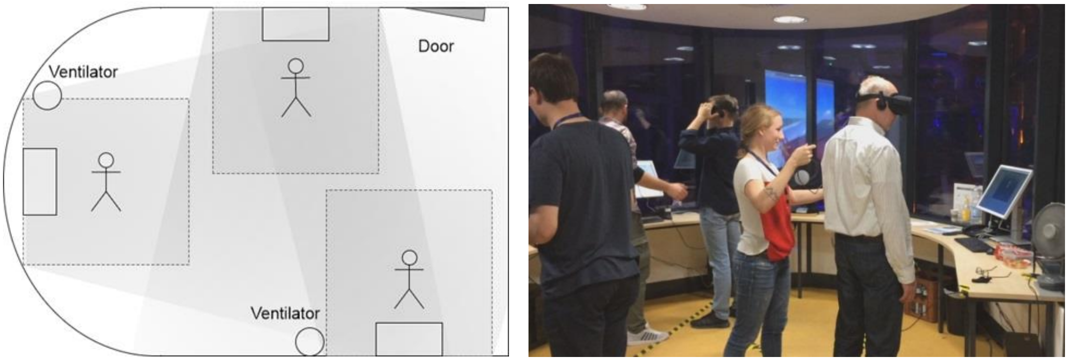
The experience starts in the dark with the ambient sound of wind, waves, seagulls and the constant drone of the turbine's rotor.

It fades into Position 1 on the lower platform, where the user faces the ladder that leads from the water surface up to the platform. The turbine's tower is situated behind the user's back and above her. The voiceover encourages her to step forward, lean over the rail and look down about 20 meters to the animated ocean surface. She can also look around, taking in the surrounding wind farm, consisting of 30 turbines, while the voiceover provides additional information. When she looks up the tower, she sees the moving rotor and real-time shadow, and a flock of seagulls at great height.

After a warning from the voiceover and a fade to black, the user is transported to the upper platform, the nacelle. She can see an open hatch in the nacelle's floor. Again, the voiceover encourages her to lean over the rail and to look down, this time about 90 meters, to the water surface.

She is now close to the moving rotor and at the same height level as the animated flock of seagulls.

After the voiceover provides more background information about the energy produced by the wind turbine, comparing it to the strength of a starting airplane, an airplane can be spotted in the direction of the rotor. It comes closer and passes over the user, in close proximity and with a loud roar. After a moment the experience ends with a fadeout.



Set-up with crossing tracking areas, exhibition space with projection screen in background

4.2. Fin Whale

Objective:

Prototype for a stationary VR installation at a museum that allows visitors to explore a historically significant, 25 m long fin whale skeleton.

“Experiencing the massive scale of a fin whale first hand”

Hardware and software: HTC Vive, Unity 3D, Autodesk Maya, Substance Suite

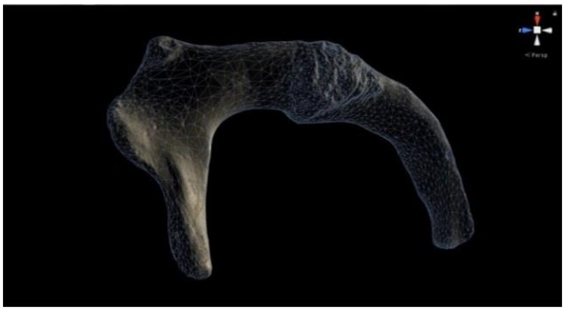
Process:

- Cleaning up and reducing the scan mesh of the fin whale skeleton (160 mio. quads)
- UV mapping and generating a procedural shader as substitute for missing textures
- Establishing a workflow to transfer the extreme mesh detail to a mid poly mesh for real-time rendering
- Lighting
- Blocking in the environment: island, rocks
- Conceptualising, testing and implementing hand interaction: Torch
- Printing and implementing hand controller (whale vertebra)
- Testing animations

Szenario (~ 5 min, walking experience)

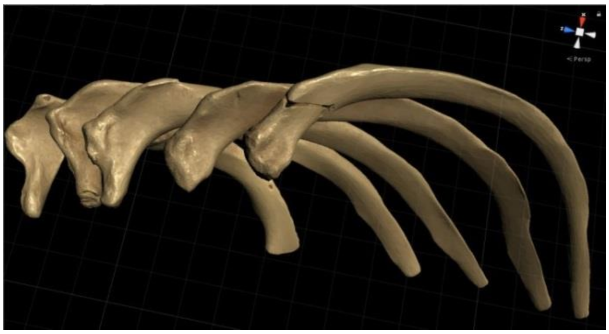
(Prototype)

- Layout and lighting indicate an underwater scenario.
- The users can move freely within a 4 x 4 m area framed by rocks.
- They can explore the whale skeleton in their own time by using a torch.
- The torch is constructed from a Vive Tracker and a printed out whale vertebra to provide haptic feedback. The torch is visible inside the VR environment as well.
- The whale will be animated to slowly “swim” above the heads of the users.
- The environment will be finalized in consultation with the museum’s scientists.
- Optional: a beating, glowing red heart will be added to the whale’s chest.

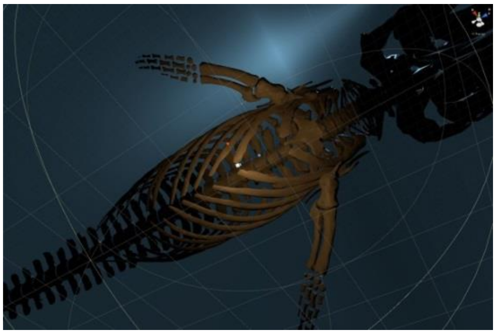


Mid-poly mesh

Transferred high poly detail, bone shader



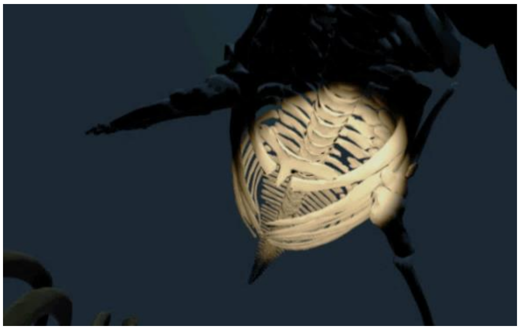
Fractured bones



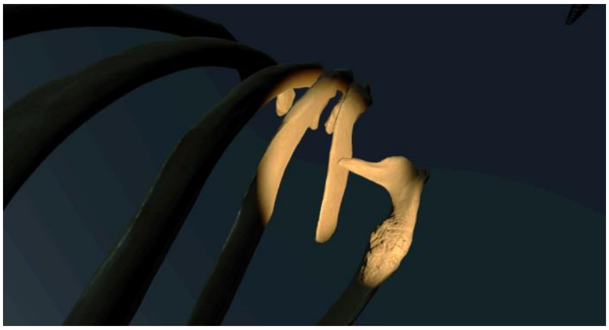
Complete mid poly mesh without detail

Bone controller "torch"

Lighting interaction



Lighting Interaction without detail



Lighting interaction: full bone detail

Implementation

The set-up is a prototype for a permanent installation at a museum of natural history (CeNak).

I chose a HTC Vive walking experience, as a closed area of 5 x 5 meter will be available at the exhibition space. The audience is diverse, with a high percentage of very young or senior visitors. Past installations have shown that these demographics have a very positive reaction to VR experiences, provided the experience is intuitive, realistic and interactive.

The main challenge of the project was to edit the scan data, supplied by the museum, for real-time rendering. The skeleton consists of 160 bones, each app. 1 mio. tris, amounting to ~ 160 mio. tris for the whole whale.

For that reason I developed a workflow to transfer the data to a reduced mesh of medium size, via a map baking processes. The scans did not have UV maps or colour data, so I UV-mapped the bones and applied a procedural bone shader that generates colour, roughness and dirt information. The workflow is tedious, as the bones vary strongly in size and need to be grouped to save texture space. All maps are 4K, to allow close inspection.

The user stands on a 4 x 4 meter island that is framed by rocks on two sides. The complete whale skeleton is placed above the head of the user and slightly tilted to the right. A directional light indicates the water surface and creates a rim light on the upper part of the skeleton.

A simple controller interaction with a torch allows the user to walk around and slowly explore the environment by lighting small areas.

The controller consists of a Vive Tracker, connected to the detailed 3D printout of a scanned whale vertebra. The tracker and vertebra are visible within the experience.

During the next phase, after consultation with scientists, a more detailed environment will be implemented and the whale will be animated to slowly move over the user’s head. Ambient underwater sound will be added.

4.3. The Outsider

Objective:

Technical prototype for an exploratory horror game, set in old castle, using photogrammetry for architectonic detail.

“Creating near-photorealistic immersion into a traditional horror film setting.”

Hardware and software: Oculus Rift CV1, Unity 3D, Autodesk Maya, Substance Suite, Agisoft Photoscan.

Process:

- Concepting and blocking in the environment
- Scouting for photogrammetry locations, photography
- Generating photogrammetry meshes and textures
- Reducing, cleaning, optimising photogrammetry meshes and textures for real-time use
- Modelling and sculpting the detailed environment
- UV mapping and creating PBR texture sets for all meshes
- Lighting
- Animating the environment*
- Implementing hand interactions for Oculus Touch controllers*

*with Heiner Schmidt

Szenario (~ 15-20 min, standing experience)

(Prototype)

- Area 1: Table with objects
    - learning to use hand controller and candle
- Area 2: Fireplace
    - lighting interactions, discovering and using objects
- Area 3: Pulley mechanism, chandelier, mural
    - lighting interaction, activation of pulley, backstory
- Area 4: Door
    - using key and leaving room

Outsider Environment (source: author).

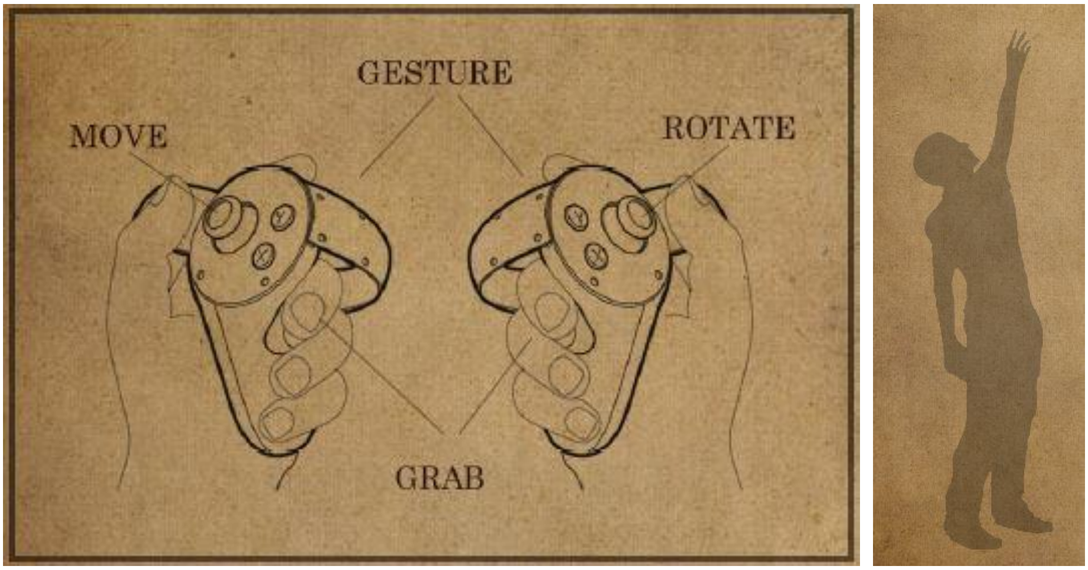
Implementation

The objective of the prototype was to create an intense “photorealistic” immersion into a traditional horror environment. It was built to test and integrate different methods for generating highly detailed and realistic surfaces and lighting in VR, such as photogrammetry, high poly sculpting, PBR materials, high quality real-time rendering of fire and shadows, and so on. These expensive methods had to be balanced with the need for a constant 90+ frames per second performance.

The environment can be used for a seated or standing experience, requiring a space of about 1.5 x 1.5 meter.

The experience starts in almost complete darkness, apart from a small candle flame that hovers in front of the user. The user needs take a candle holder and catch the flame. Afterwards she can use the candle to examine the objects on the table in front of her in great detail. She can also pick up the objects and interact with them, for example open them and so on.

The room has several interactional areas that can be explored: At the fireplace the user can discover and use a number of objects, to light the fire. Near the door, she can light a chandelier and trigger the pulley system that lifts it up to the mural. She can use a key to open the door. While the experience works both seated and standing, at one point the user is encouraged to stand up and reach for an object at great height.



Oculus Touch controllers, standing interaction (source: author).

4.4. Rotation Room

Objective:

Building an environment for an experimental room that allows walking-in-place on walls and ceiling.

“Experiencing spatial rotation in VR.”

Hardware and software: HTC Vive, Unity 3D.

Process:

➔ Rotational walking-in-place tool developed by Jonathan Becker

- Furnishing the environment in such a way that it supports the experimental set up
- Lighting

Szenario (~ 5 min, walking experience)

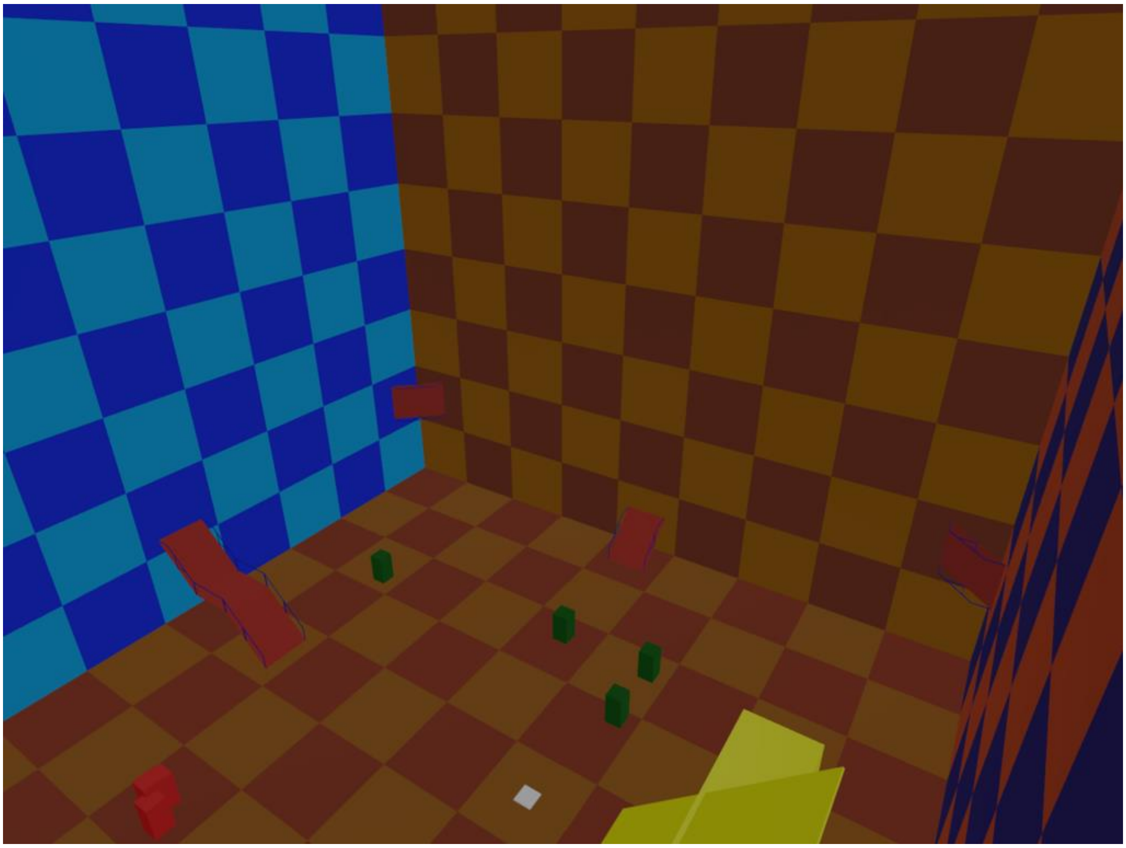
(Prototype)

- The user starts in the middle of the room inside the cage
- She walks physically to the edge of the cage
- Reaching the cage’s boundaries triggers animated cage movement
- The cage moves towards and up the lower and upper ramp
- The user “rotates” with the ramps
- The user walks on the walls and the ceiling
- The user returns to the initial position using the opposite ramps

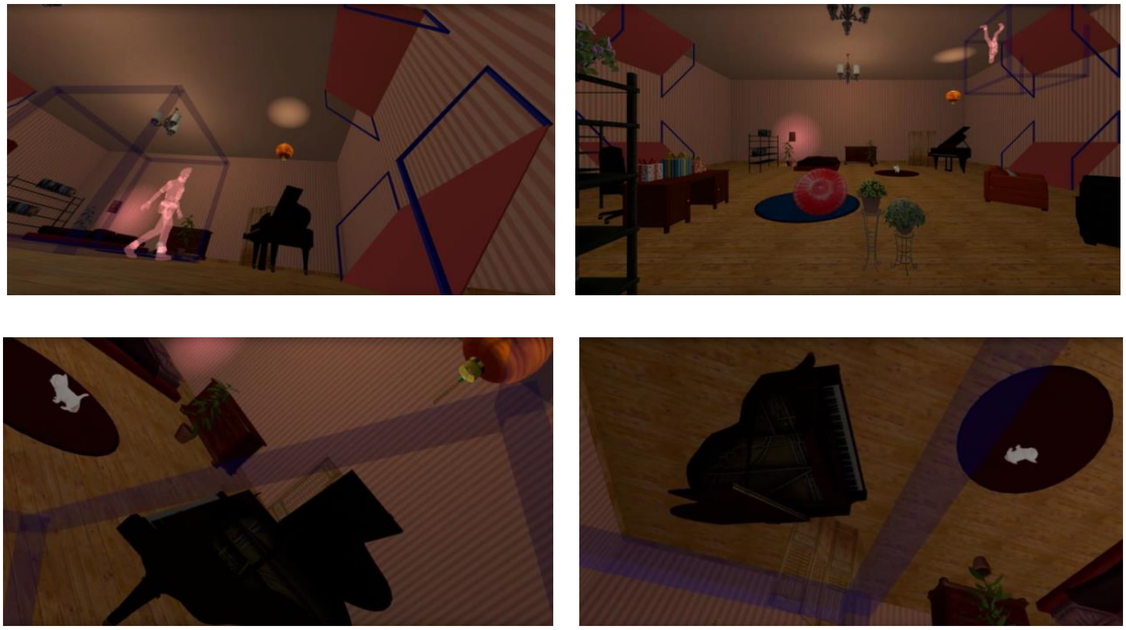
Implementation

The application was built by Jonathan Becker for his Bachelor Thesis to allow rotational walking-in-place.

To support spatial orientation and rotation, I omitted the regular checkered pattern that covered the whole environment. Instead, I implemented a distinct wood texture for the floor, striped wallpaper for the walls and a plain white ceiling. Instead of an ambient light, I placed several spot lights. I covered the floor and walls with irregular furniture and added an animated cat.



The initial environment (source: Jonathan Becker).



Scenes from the final environment, rotation, ramps, cat (source: author).

5. Discussion

The following part analyses and discusses the sensorimotor contingencies and sensorimotor affordances of the environments presented in Part 4, by using the established models and framework. It demonstrates that the framework is robust and versatile enough to plan, describe and interpret different types of VR environments.

Additionally, this part integrates early user reactions into the discussion. So far, each application has been tested by ca. 100-200 alpha testers, during public and semi-public events. User age varied between about 5 years and 80+ years; a high percentage of users had never worn a VR headset before.

5.1. Position, scale, layout and self-movement

When building a VR experience for a public exhibition, the audience, the time frame and the available space usually determine the spatial-temporal layout of the environment. The virtual *Wind Turbine* was built to scale for an event with several hundred visitors. Only a small walking space and a restricted time frame were available. This meant that users would not be able to explore the huge wind turbine fully by way of self-movement. To keep the learning curve low and to reduce the risk of motion sickness, I decided against the use of animated movement or teleportation. Instead I implemented a scene with multiperspection, consisting of two meaningful positions: one on the lower platform, and one on the nacelle, about 90m above sea level. The contrast in height between these positions provides an immersive experience of the massive scale of the wind turbine, despite spatial-temporal restrictions.

The stratification of the rail in the foreground, the larger parts of the turbine in the middle ground and the surrounding wind turbine field in the background affords depth perception and orientation within the otherwise uniform ocean environment. The motion parallax between foreground elements (the rail) and background elements (the water surface) affords information about self-movement.

Physically walking on the lower platform within the 2 x 2 meter area allows the user to estimate the tower’s scale, in relation to her stride length. When bending over the platform’s rail, scale is further established through the use of self-movement, both in relation to the rail’s height, i.e. the user’s waist height, and in relation to the animated water surface about 20 meters below the platform.

Seeing the ladder that leads down to the water surface serves as retroactive action activation, explaining how the user got on this platform, possibly by climbing up from a ship that is no longer in sight.

Turning around, the user will see the tower, including an affordance for action activation, in the form of a door that seems to lead upstairs. Her attention is further directed up the 90 meter tower by the huge moving shadows of the rotor blades. Her eyes and ears are drawn to the upper platform by a distant, screeching flock of seagulls wheeling up there. The size of the birds affords an additional natural scale in relation to the height of the wind turbine.

Similar to the *Wind Turbine*, the *Fin Whale* VR experience was commissioned for a full scale exhibition of the museum’s fin whale skeleton. With a length of ~ 25 meters it is too big to install inside the existing museum space. Therefore experiencing scale was the main objective of the project.

The first concept had users walk inside the skeleton’s rib cage, but that version had to be scrapped after consultation with scientists. Fin whales are very slender and their ribcages are “folded in” when they swim, meaning that the skeleton is too low to properly stand in.

To provide a strong affordance for height without changing the scale I moved the user about 2 meters below the skeleton’s head. I tilted the full skeleton slightly around the long axis, to decrease balance and simulate movement. Standing below the tilted, full-length skeleton also simulates gravity and weight (“what if it fell down on me?”).

To emphasise length, I pointed the skeleton away from the user. This view also created stratification and increased depth perception within the otherwise empty space, through the overlapping bones and converging angles and lines.

Walking freely below the skeleton within a 4 x 4 meter tracking area allows users to measure and understand its scale physically, in relation to their own body scale and stride length.

While the user can walk within the tracking area, the whale is a lot longer than that. Seen from the tracking area, the whale’s full length is estimated shorter than it actually is. This is not surprising as length is regularly underestimated in VR. To compensate for that, during the next iteration the skeleton will be animated to swim very slowly over the users’ head, providing her with affordances for a realistic assessment of its length. Environment elements such as small fish and water particles will serve as natural scale.

The *Rotation Room* was built for walking-in-place and head-over-heels rotation within a VR environment, i.e. the main objective was locomotion in all directions, and rotation around the x axis. A tracking area of 5 x 5 meter was available. I was asked to create a full environment for the room, which was initially textured with a uniform checker pattern. To increase orientation I replaced the checker pattern with textures that provide clearly defined spatial affordances: wood for the floor, wallpaper for the walls and a uniform white colour for the ceiling. I chose a striped pattern for the wallpaper to further indicate verticality and gravity. Vertical shelves did not reach the ceiling to clearly distinguish top from bottom and to anchor them to the floor. Lamps hanging from the ceiling provide more affordances for gravity.

To simulate gravity and weight, objects were chosen for their perceived differences in weight, e.g. the grand piano versus the paper umbrella. Movable light objects, such as books, plants and cardboard boxes were placed and piled on heavier surfaces such as tables and shelves. While the objects could have been glued to surfaces, a living, moving object could not. Therefore an animated cat was added as “proof” for gravity.

The white, moving cat on the eye-catching round blue carpet also served as a landmark that is visible from all positions. To further increase orientation and provide landmarks, the layout of the furniture was irregular, with defined areas that afforded stratification throughout the room.

The animated cat seemed to provide strong action activation for self-movement and induced unplanned interactions, as users tried to stroke the cat and play with it. The “living”, animated creature within an otherwise static environment seemed to anchor users and increase immersion.

5.2. Balance and animated movement

Standing on the lower platform of the *Wind Turbine* and looking up to the nacelle, the user is fully aware of its height, so that “beaming” her up to the nacelle for the next scene is expected to have a strong impact. Users with vertigo and fear of heights were physically affected, struggling for balance, especially during earlier iterations, when the rails on the nacelle were not yet installed. The rails seem to afford purely visual stabilisation in relation to gravity, as no haptic feedback was available. While all users were aware that the “abyss” was only virtual, as they could feel the floor beneath their feet, most were strongly reluctant to step over the ledge of the platform. Similar reluctance could be observed in the Fin Whale experience, where users avoided stepping over the boundary of the “island”. But a small group of users took the opportunity to spontaneously experiment with their fear of heights by stepping from the platform into “thin air”.

Even with the rail installed, bending over and looking down about 90 meters to the lower platform, and to the ocean’s surface, affected user balance. Most users seemed to experience action activation that led to a fear of falling and trying to take hold of the rail.

The vestibular sense is also strongly affected by animated user movement or rotation, as is present in the *Rotating Room*. The translational animation is triggered when the user walks physically to the boundaries of the “cage”. After touching the boundary, the cage “glides” towards the rotation ramp and initiates animated rotations of the user, who then glides up the wall, and along the ceiling.

The new, more spatialised environment seemed to strongly increase immersion during animated rotation. The animation induced physical sensations of rotation (vection), bordering on a rollercoaster feeling. Users struggled to keep balance, especially during the “tipping point” of rotation between floor and wall, and between wall and ceiling.

It is obvious that the observed simulation of vestibular sensation is induced by the visual input from the environment. The apparent increase of vection within the new environment, as compared to the older environment, suggests that an increased visibility of gravitational affordances by way of layout and texture may be the cause. While the older environment had clearly defined vertical cues only in the corners of the room, the new environment provided orientational cues in all directions, i.e. the user sees gravitational affordances from every position, at every moment.

Simulated vestibular sensation, including loss of balance, was mainly observed during animated rotation, but not while walking on the ceiling. This was probably due to the fact that the contradiction between visual input from the HMD and physical gravitational input from proprioceptive haptic and vestibular senses was too strong, and prevented users from physically experiencing an up-side down position.

Self-movement and animated movement were experienced differently within the *Rotation Room*. While self-movement within the 5 x 5 meter tracking area was experienced as natural and unproblematic, walking-in-place through user animation and animated rotation caused vection, which in some cases was a trigger for motion sickness.

Similar reactions could be observed in *The Outsider* where self-movement was restricted to a small seated or standing area of about 1.5 x 1.5 meters. The user can move physically within a seated or standing position, i.e. she can turn around, bend down or reach out. But locomotion is controlled with the Oculus Touch controllers and simulated by animation. While increasing the risk of motion sickness, animated locomotion also decreases immersion. To counteract motion sickness, speed was reduced to a slow walking pace and acceleration and rotation were strongly controlled. Immersion is increased through the implementation of affordances for intense physical interactions, such as standing upright and using a tool for reaching objects in great height.

5.3. Surface, lighting and interaction

For the *Wind Turbine*, the customer asked for the visualisation of an existing CAD model. As the model was highly detailed (including all screws) and not built for a real-time render engine, it needed to be heavily reduced and re-organised. It also did not contain UV maps. Due to time constraints, I decided to use a simple shader without surface detail, and to build the lighting and texturing of the environment around this. I implemented a strong, almost vertical sunlight to overexpose the environment and “explain” the lack of detail shadows on the wind turbine. To encourage filling-in of the missing surface detail, I built a detailed, near-photorealistic sky and ocean.

The ocean’s real-time specularity provides affordances for self-movement and stereoscopic vision. Shadows were also set to real-time, to make use of the enormous animated rotor shadows that swipe rhythmically over the user and the whole environment.

The main objective of the set-up was to create an immediate experience of the massive, but invisible energy produced by the turbine. To avoid abstractions such as visualisations or diagrams, this is achieved by mapping the energy of the turbine through the forces of nature, mainly the wind, ocean and sun, and the scale, movement and sound of the environment. The energy’s effects on air, water and rotor, i.e. movement and sound, stand in for their source, i.e. they map it metonymically.

I further used the smooth surfaces, strong bright light and dominant colours white and blue to simulate a cool temperature by filling-in, and to map metonyms for ENERGY and CLEANLINESS.

For the *Fin Whale* experience, keeping the full detail of the skeleton’s scan data was vital for scientific purposes. Its detail and aging also transport meaning, for example some bone fractures have a historically significant backstory.

To encourage an interactive exploration of detail, I implemented a hand controller interaction with a Vive Tracker, functioning as a torch. By using the torch as a tool that extends the arm’s reach, the users “reach out” and “touch” the skeleton to spatially explore and understand its forms and details with light.

That way the tool mediates the use of sensorimotor contingencies, such as self-movement, stereoscopic vision and light and shadow behaviour, to slowly explore the skeleton within the otherwise dark

environment. The bone shader’s roughness map generates real-time specularity which functions as a sensorimotor affordance for self-movement and light behaviour in space.
Touching the skeleton with light instead of virtual hands also avoids the potential disconnect caused by missing haptic feedback.

Most VR environments, even AAA games such as *The Climb* (Crytek 2016), fail to provide detailed surfaces. The main reason for this is that normal maps, which are used in computer games to keep real-time render budget low, do not work properly in VR. When the interaction brings the user in very close contact with surfaces, as is the case in *The Climb*, this can break immersion, as the surface detail looks flat in close proximity and from steep angles.
The environment in *The Outsider* was built with surfaces that hold up to close-up inspection of < 10 cm. The surface detail provides affordances for self-movement and stereoscopic vision, such as mesh detail and micro detail. It also reacts realistically to moving, real-time light, as it contains maps that control roughness, reflectivity and so on. These surface maps, in combination with real-time shadows, function as affordances that provide information about self-movement, the light situation and so on.
The hand controllers allow the user to hold and naturally move a candle. That way the user can take full advantage of light-related sensorimotor contingencies to experiment with light, specularity and shadow, while examining objects and exploring the environment. To examine objects, users can use self-movement of the head and body, and coordinated spatial hand movements by holding the candle in one hand and an object in the other.
Through filling-in triggered by surface properties, the user understands the materiality of the object, its haptic qualities, such as its weight, which can lead to action activation. Users can study the wear and tear on objects or discover hidden detail such as inscriptions, to gather information about the age and backstory.

PBR surfaces, candle interaction and mesh detail in *The Outsider* (source: author).

Darkness and light are employed as the main affordances to map valence (LIGHT is GOOD, DARK is BAD) and to trigger affect. This valence mapping is also used to spatially and temporally structure interaction through lighting. The prototype starts in almost complete darkness, with only a small candle flame. The user explores the environment gradually and by lighting candles and fire, while avoiding the darker areas. The reflective surfaces and small light sources, such as glowing coals in the fireplace, serve to direct attention and guide spatial self-movement through action activation.

5.4. Sound and haptics

Sound was a strong affordance for the *Wind Turbine*, for providing information and directing attention. The powerful energy source of the turbine, i.e. the wind, and its effects were ever present in the constant howl of the storm, the roaring waves of the ocean and the rhythmical drone of the moving rotor. The sound also provided spatial immersion and orientation by surrounding the user with loud sound sources at different positions in space.

The “radio” voice over was used to avoid abstract text displays for providing technical information, which might have decreased immersion. It also structured the experience spatially and temporally, by asking the user to look in specific directions and to prepare her for “beaming” to another position. By this the voiceover also ensured a smooth progress during the exhibition.

Adding physical haptic input to the visual, audio and proprioceptive input of a VR experience strongly increases immersion. But physical haptics are also susceptible to break immersion, if they are not implemented carefully. During the exhibition of the *Wind Turbine*, haptic cues for wind and cold temperature were generated by way of a ventilator. While the ventilator was successfully added in other applications, in this case it proved too weak to fully line up with the loud ambient sound of the wind. As multimodality of perception is initiated by similarities of factors such as intensity, it seems that a discrepancy in intensity can cause a mild break of immersion.

The Vive Tracker of the *Fin Whale* experience was attached to a 3D printed vertebra of the skeleton, to provide haptic feedback. Both the tracker and the vertebra are also visible within the virtual environment, creating a strong association between the physical and the virtual object.

Interestingly, the fact that the controller is both haptically felt and visible, but the hand that touches it is felt, but not visible, causes a mild break of immersion (“my hand is gone”). This was not the case in earlier iterations when the controller was invisible, and the invisible hand was accepted. During the next iteration, I will implement a tracked hand to remedy that problem.

6. Conclusion

6.1. Summary

Understanding the underlying rules of perception and parameters that are at work in complex VR environments has become more important since the availability of consumer market, real-time rendered, VR applications, for example for different types of commercial and scientific visualisations and computer games. This study has argued that research in the context of HCI and related fields mainly focuses on questions of virtual embodiment, and on single-factor studies, while complex, multi-factorial VR environments are relatively underresearched.

The lack of research is problematic for environment designers, as VR is a medium that strongly affects the body, and due to its medium specificity, creates a unique experience of place illusion, i.e. the illusion that the user is physically present within the virtual environment. This means that design rules and techniques from other audiovisual media, such as 3D films and computer games, can be transferred only to a limited degree to VR.

To better understand the medium specificity of VR, this study discussed the historical development of spatially immersive technologies such as 2.5D, panoramas, and tracking. As Slater (Slater, 2009) shows, it is the specific combination of spatially immersive technologies within VR systems which creates place illusion, by allowing users to apply sensorimotor contingencies for perception. Sensorimotor contingencies are defined as the implicit rules of how self-movement is used for perception.

Sensorimotor models of perception and experience therefore stress the importance of self-movement for perception, so that this study concludes that rotation and especially translation tracking is probably the defining contingency of VR, turning VR into a “sensorimotor medium”.

The study described the sensorimotor loop, i.e. the model of a feedback loop between the body’s sensorimotor system and environmental factors, and proposed to distinguish sensorimotor contingencies inherent in the environment from sensorimotor contingencies inherent in the body, by introducing the term *sensorimotor affordances*. The term *affordance* was first coined by Gibson to emphasise the lawful unity of an organism and its environment during perception, and to describe the perceived interaction possibilities inherent in an environment (Gibson J. J., 1986).

The concept of sensorimotor affordances was then applied to integrate and interpret divergent results on the effect of surface and rendering properties on physiological parameters and presence in VR (Hvass, Larsen, Vendelbo, Nilsson, Nordahl, & Serafin, 2017) (Toczek, 2016) (Yu, Mortensen, Khanna, & Slater, 2012) (Zimmons & Panter, 2003).

The thesis concluded that building environments for VR means building sensorimotor affordances.

Adapting Ward’s (Ward, 2015) pioneering approach to sound design for VR environment design, the study presented and explained different techniques of *perceptual design*, i.e. the generation of information, simulation and spatial-temporal structuring by affecting the sensorimotor system. To show

how information about the self, the environment and self-movement is generated in VR environments, the study discussed the physiology of perception through VR’s sensorimotor contingencies. It explained different mechanisms of sensory, neural and cognitive simulation and mapping, and applied them to VR. It then discussed and problematized the options for spatial-temporal structuring in VR within the context of different media systems.

These results were applied to show how specific environmental affordances, for example surface specularity, can be utilised to generate information, and how this information forms the basis for simulation and spatial-temporal structuring within VR environments.
The results were then integrated into a framework of basic environmental affordances, including position, rotation, scale, layout, surface properties, and lighting, in combination with movement and interaction, and additional parameters such as sound and haptics. Their application for generating information, simulation and spatial-temporal structuring in VR environments was discussed in detail.

The practical part of the study presented four different VR environments, a technological *Wind Turbine* simulation for a public exhibition, an interactive *Fin Whale* experience for a museum, a photorealistic environment for a horror game, and a scientific application for rotation simulation in VR.
These environments were analysed and discussed by making use of the established models and framework. The analysis provided a wide range of insights, for example into how position, scale, layout and self-movement interact in VR environments, how the vestibular sense is affected by heights, animated rotation and translation, how surface properties and lighting relate to interaction, and what role haptics play for VR environments.
It was shown that the framework is versatile and robust enough to describe and understand different types of environments, and to provide designers with guidelines for VR environment design.

6.2. Future research

The sensorimotor framework for VR environments developed in this study provides an overview of the underlying rules of perception (or sensorimotor contingencies), and of the basic parameters (or sensorimotor affordances) of VR environments. While it cannot replace studies that investigate isolated environmental factors, it can help to identify and clarify research questions, and integrate existing and future research.

The findings of this study raise basic questions about the role of environmental parameters for perception in VR. If Gibson was right and bodies and environments form a unity during perception, then how does this relate to perception within a mediated, illusionary environment like VR? Are VR environments just “content”, or do they constitute perception in some way? And how does the concept of sensorimotor affordances relate to Slater’s concepts of place illusion and plausibility illusion?

The combination of sensorimotor models of perception with Gibson's model of affordances, and with neurocognitive approaches such as Conceptual Metaphor Theory, as it was attempted here, seems productive not only for the analysis of VR environments, but also for other design disciplines that work with complex environments, such as game design or theme park design.

From the VR designer's perspective, the sensorimotor framework can provide a first guideline for understanding and interpreting practical observations during design and testing processes, and help to make effective design decision that work with the medium specificity of VR, not against it. The relatively open nature of the framework encourages future additions and extensions.

The framework not only constitutes a first attempt to collect and systematise functional design techniques for VR environments, but it is also a more general attempt at formulating a theory of perceptual design for VR. As such, it intends to be part of a future, systematic investigation of design processes in different media systems, as it was suggested by Bundgaard (Bundgaard, 2014) and realised by Ward (Ward, 2015). In short, this study hopes to contribute tools for implementing a feedback loop between design processes and scientific investigations.

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8. List of figures

Declaration of Authorship

I hereby certify that this thesis has been composed by me and is based on my own work, unless stated otherwise. No other person's work has been used without due acknowledgement in this thesis. All references and verbatim extracts have been quoted, and all sources of information have been specifically acknowledged.

Date: Signature: