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The Integration of Virtual Reality into the Design Process

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As designers, we have a great responsibility.
I believe designers should eliminate the unnecessary.
That means eliminating everything that is modish
because this kind of thing is only short-lived.

— *Dieter Rams*

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Abstract

Technological advances strive towards automation and digitalization with the aim to increase efficiency in terms of decreased costs and product development time, resulting in shorter product life cycles. As this causes industries to release products more frequently and more quickly, industrial designers face problems in developing more complex systems in a decreased amount of time while aiming to meet individualized user requirements and stakeholder demands. If prototypes are infeasible or unaffordable, a successful market implementation of products is jeopardized. As design history proves, the introduction of new technologies to the profession of design has the potential to revolutionize the way of working for industrial designers. Virtual Reality may be one of these revolutions, as Computer-Aid Design has been in the 1980s. The present dissertation investigates the integration of Virtual Reality and its impact on the design process, the respective design method, but also the designer and design as a profession.

After defining industrial design and Virtual Reality, a basic framework is proposed that describes a design process consensus model, the transfer of conventional design methods into VR, as well as a preliminary set of criteria for evaluating design studies. Based on this framework, four research questions are defined that initiate the investigation of how Virtual Reality can impact the design process, design methods, the role of designers, and design as a profession. To allow this, a refined set of criteria for evaluating design studies is developed and a benchmark study is conducted that proves the suitability for using Virtual Reality in the chosen context. Subsequently, five design studies are conducted in the field of autonomous mobility for public transport in Singapore to investigate the previously defined questions. The five design methods that are combined with Virtual Reality are heuristic evaluation, surveys, Computer-Aided Design prototyping, usability testing, and product presentation. For each design study, the development of the VR apparatus as well as the data collection and test of the method is explained. Additionally, two conventional design methods are consulted for a subsequent comparative analysis of each VR methods.

Beyond the definition of the refined evaluation criteria, consisting of safety, validity, time and cost, variability, interactivity, immersion, and effort, the suitability of using VR for behavioural observation in the present application domain is confirmed.

Based on the present investigations, the Virtual Design Toolbox is presented. The toolbox consists of five method cards that explain the usage of Virtual Reality for industrial designers throughout the product development and function as support for successfully developing and applying design methods utilizing this technology.

The case studies prove that the usage of Virtual Reality has the potential to impact the design process, as divergent thinking and convergent thinking is fostered through valid data collection, decreased time- and cost- involvement, and increased variability. The roles of the involved designers throughout all design studies shifted from being concept creators towards coordinators and facilitators. Implications are derived on different levels, starting with the technology of Virtual Reality that could be a future game changer for research and design, followed by increased motivation to participate in design studies, the need for interdisciplinary teams to establish the required expertise, and lastly integration of Virtual Reality in design education. The usage of Virtual Reality in design will not replace conventional design methods but has the potential to lead to a paradigm shift for the whole profession of design.

Zusammenfassung

Der technologische Fortschritt entwickelt sich in Richtung Automatisierung und Digitalisierung, was zu erhöhter Effizienz und damit zu verkürzten Produktentwicklungszeiten und verkürzten Produktlebenszyklen führt. Da dies die Industrie dazu veranlasst, Produkte häufiger und schneller zur Marktreife zu bringen, stehen Industriedesigner vor dem Problem, komplexere Systeme in kürzerer Zeit entwickeln zu müssen und gleichzeitig die individuellen Anforderungen der Nutzenden und anderer Stakeholder zu erfüllen. Wenn Prototypen nicht fertigbar oder nicht bezahlbar sind, ist eine erfolgreiche Markteinführung gefährdet. Wie die Designgeschichte beweist, hat die Implementierung neuartiger Technologien in den Beruf des Designers das Potenzial, die Arbeitsweise des Industriedesigners zu revolutionieren. In der vorliegenden Dissertation wird daher die Integration und die Auswirkung von Virtual Reality auf den Designprozess, Designmethoden, aber auch den Designer und das Design als Profession untersucht.

Nach der Definition von Industriedesign und Virtual Reality wird ein grundlegendes Vorgehen vorgeschlagen, das ein Konsensmodell für den Designprozess, die Übertragung konventioneller Designmethoden in die VR sowie vorläufige Evaluierungskriterien zur Bewertung von Designstudien beschreibt. Basierend auf diesem Vorgehen werden vier Forschungsfragen definiert, die die Untersuchung einleiten, wie Virtual Reality den Designprozess, Designmethoden, die Rolle von Designern und Design als Profession beeinflussen kann. Um dies zu ermöglichen, wird mit Hilfe von Experteninterviews ein ausgearbeitetes Set von Evaluierungskriterien zur Bewertung von Designstudien entwickelt und eine Benchmark-Studie durchgeführt, die die Eignung für die Verwendung von Virtual Reality in der gewählten Applikationsdomäne belegt. Anschließend werden fünf Designstudien im Bereich autonomer Mobilität für den öffentlichen Verkehr in Singapur durchgeführt, um die zuvor definierten Forschungsfragen zu untersuchen. Die fünf Designmethoden, die mit Virtual Reality kombiniert werden, sind heuristische Evaluation, Umfragen, Computer-Aided-Design Prototyping, Usability-Tests und Produktpräsentation. Für jede Designstudie wird die Entwicklung des VR Apparats sowie die Datenerhebung und der Test der Methode erläutert. Zusätzlich werden zwei konventionelle Designmethoden für eine anschließende vergleichende Analyse herangezogen.

Nach der Definition der verfeinerten Bewertungskriterien, bestehend aus Sicherheit, Validität, Zeit und Kosten, Variabilität, Interaktivität, Immersion und Aufwand, wird die Eignung der Verwendung von Virtual Reality zur Datenerhebung in der vorliegenden Anwendungsdomäne bestätigt.

Basierend auf den vorliegenden Untersuchungen wird die Virtual Design Toolbox vorgestellt. Die Toolbox besteht aus fünf Methodenkarten, die den Einsatz von Virtual Reality für Industriedesigner während der Produktentwicklung erklären und als Unterstützung für die erfolgreiche Entwicklung und Anwendung von Designmethoden mit dieser Technologie dienen.

Die Fallstudien belegen, dass der Einsatz von Virtual Reality das Potenzial hat, den Designprozess zu beeinflussen, da divergentes und konvergentes Denken durch valide Datenerhebung, verringerten Zeit- und Kostenaufwand und erhöhte Variabilität gefördert wird. Die Rollen der beteiligten Designer verschoben sich in allen Designstudien von der Rolle des Konzepterstellers hin zum Koordinator und Moderator. Implikationen werden auf verschiedenen Ebenen abgeleitet, beginnend mit der Technologie von Virtual Reality, die ein zukünftiger Game-Changer für Forschung und Design sein könnte, gefolgt von der gesteigerten Motivation, an Designstudien teilzunehmen, der Notwendigkeit interdisziplinärer Teams, um die erforderliche Expertise zu etablieren, und schließlich der Integration von Virtual Reality in die Designausbildung. Der Einsatz von Virtual Reality im Design wird herkömmliche Designmethoden nicht ersetzen, hat jedoch das Potenzial, zu einem Paradigmenwechsel für das gesamte Berufsfeld des Designs zu führen.

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List of abbreviations

3D	Three-dimensional
AR	Augmented Reality
AV	Autonomous Vehicle
CAD	Computer-Aided Design
CAVE	CAVE – Automatic Virtual Environment
CREATE	Campus for Research Excellence And Technological Enterprise
DART	Dynamic Autonomous Road Transit
DGS	Dynamic Guidance System
DoF	Degrees of Freedom
HCD	Human-Centred Design
HMD	Head-Mounted Display
ImPro	Immersive Prototyping
MR	Mixed Reality
MRT	Mass Rapid Transit
NRF	National Research Foundation
NTU	Nanyang Technological University
OEM	Original Equipment Manufacturer
PP	PowerPoint
TAM	Technology Acceptance Model
TUM	Technical University of Munich
VR	Virtual Reality
UI	User Interface
UX	User Experience
XR	Extended Realities

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1 Introduction and objectives

1.1 Problem statement and relevance

Subsequent to the mechanization (first industrial revolution), the utilization of electric energy (second industrial revolution), and digitalization (third industrial revolution), Industry 4.0 constitutes another paradigm change and forms the fourth industrial revolution (Lasi et al., 2014). The levels of automation and digitalization change product development processes in the way that fast development cycles as well as short product life cycles are expected (Lasi et al., 2014). Therefore, industries are encouraged to release products more frequently in order to stay competitive, with the objective to meet the growing needs and customer expectations. These customer needs and wants need to be rigorously understood to define design requirements accordingly. However, user needs and expectations are constantly changing (Hintersteiner, 2000) and customers are striving towards individuality, which is often expressed via products (Chapman, 2012). This raises problems: Industrial designers aim to design products, services, experiences, and businesses according to user needs, while meeting market demands and considering economic, social, cultural, and ecological aspects (Heufler, 2004). In the present dissertation, the term “industrial design” is used with the meaning of the activity an industrial designer carries out to develop products out of an underlying problem statement, need, or idea. The result of the activity is supposed to fulfil user needs as well as needs for all involved stakeholders. During the development, the designer has to be aware of different aspects like technology, ergonomics, sociology, ecology, psychology, philosophy, and finance. All these aspects have to be considered in the context of development time and the intended application domain (cf. chapter 2.3 Definition of industrial design). The term “product” in this dissertation summarizes all possible outputs designers produce including services, systems, experiences, and businesses.

For each project, unique criteria have to be considered, including aspects such as safety for all involved stakeholders, the collection of valid data, and time- and cost-efficiency that the involved designers need to respect. Taking Industry 4.0 and the resulting accelerated product development into account, industrial designers have to **design more complex products in a shorter period of time while having to meet the aforementioned criteria and user requirements**. Moreover, optimal functionality, usability, and ease of use must be ensured for user acceptance and a successful market implementation (Davis, 1989). If prototypes are not available, feasible, or affordable, a successful market implementation of products is jeopardized. Researchers already foresaw these upcoming challenges in the 1980ies, as for instance Jones (1981) predicted that our reality is becoming increasingly more complex and thus new design methods are required for dealing with that complexity.

1.2 Scope and aim

The focus of the present dissertation is the investigation about how the technology of Virtual Reality can address and potentially solve the aforementioned problems that arise due to the accelerated product development process by allowing enhanced problem identification, ideation, conception, evaluation, and presentation of products. Therefore, **the overall aim of this work is to investigate the impact that Virtual Reality can have on industrial design**. This includes the investigation on the impact of Virtual Reality on design studies, the design process, and the role of the involved designers. The following questions will be answered in the present dissertation to achieve the aforementioned aim:

How does the combination of design methods with Virtual Reality impact design studies as well as the involved designers? By answering this question, it is planned to make an attempt in assessing the impact or Virtual Reality on industrial design.

Which criteria are needed to allow a comparison of design studies in a specific application domain? To answer this question, a framework will be developed (i.e., through evaluation criteria) that allows assessing the advantages and drawbacks of using specific design methods.

To which extent can Virtual Reality trigger authentic behaviours and reactions of participants in a specific application domain? By answering this question, the suitability of using Virtual Reality as a valid data collection tool in the present application domain will be verified.

The term “Virtual Reality” (VR) refers to a computer-generated simulation that users can experience. In the present dissertation this exclusively refers to head-mounted displays (HMD) that allow these virtual experiences and therefore excludes CAVE technology and tactile equipment (e.g., gloves). The term “design studies” refers to projects that were carried out by designers in order to develop products. While carrying out design studies, designers follow the design process. The term “design process” describes the stages designers absolve including activities and approaches taken by the designers during that endeavour. During the design process, the designers apply “design methods” (i.e., procedures and techniques) for defining problems, ideate, develop solution approaches, and evaluate concepts.

The term “impact” refers to the positive and negative effects that VR has on the outcome of design studies, design methods, the design process, and the role of the designer. “Designer” in the present dissertation refers to an industrial designer, graduated from a university in the field of design, who is employed in a design department of a company that incorporated the profession of design in its product development and strategy. “Evaluation criteria” describe relevant aspects for a used design method in order to measure its benefits and limitations compared to other design methods.

Based on the present investigations, a method card toolbox for industrial designers for using VR design methods will be developed as basis for further research but most importantly as a tangible outcome that can be directly applied by industrial designers.

1.3 Context: TUMCREATE and DART

TUMCREATE is a research institute that is founded by the Technical University of Munich (TUM), Germany and the Nanyang Technological University (NTU), Singapore. TUMCREATE’s mission is to seek the ultimate public transport system for Singapore that provides highest comfort and an optimal travel experience while ensuring environmental protection and maximum benefit for Singapore’s society and economy through a vision of public transport of electric autonomous vehicles from 2030 onwards (TUMCREATE, 2019).

TUMCREATE’s proposed traffic system is called “Dynamic Autonomous Road Transit” (DART) and consists of fully electric level 5[1] autonomous road-based busses with a capacity of 30 passengers (40% seating, 60% standing). DART builds a layer between the rail-based Mass Rapid Transit (MRT) that offers high capacity and fast speed, but a sparse network and the road-based bus system that has relatively low capacity and slow speed but a dense network of stations. TUMCREATE follows a system-level approach which means that beyond the vehicle engineering and design (including the development of the power train, interior, and exterior), the development includes infrastructure (i.e., bus stops and transit hubs), electrification of the vehicle and power grid for seamless charging, traffic monitoring, and a centralized system to operate the fleet (TUMCREATE, 2019).

[1] While in level 0 autonomous vehicles, a human driver has to perform all driving tasks, level 5 automation refers to a system in which humans do not overtake of influence any driving tasks in any situation, but solely act as passengers (SAE International, 2016)

Figure 1. Dynamic Autonomous Road Transit (TUMCREATE, 2019)

DART incorporates a set of unique features that allows a fast, convenient, and efficient mode of transport. These features include *Platooning***.** When driving on main roads (called corridors) the DART vehicles can drive closely behind one another in a platoon of up to ten vehicles. This reduces drag and traffic space between the vehicles and allows passing of junctions more quickly. When reaching suburbs, the vehicles from each platoon can split up in order to serve separate end destinations. Another feature is *Traffic control***.** In order to make DART's operation more efficient and increase its average speed, traffic lights are controlled in a way so that DART vehicles have minimized waiting times. A further feature is called *Virtual right of way*. Singapore's land space is limited which does not allow dedicated lanes for DART. Therefore, the most left-hand lanes on multi-lane roads are used for DART. To optimize the efficiency of overall traffic, other road users are allowed to use these lanes as well. As soon as a DART vehicle or platoon is approaching, other vehicles are notified to clear the lane in order to let the DART vehicle or platoon pass.

In addition to the development directly connected to the vehicle and infrastructure, one research focus of TUMCREATE is the user-centred design of DART for Singapore including aspects as the improvement of comfort and travel experience when travelling with DART and the impact of the absence of drivers in the automated system on the travel experience (Cornet et al., 2019).

These challenges include scenarios such as:

- The **communication** between **pedestrians and DART** in ambiguous situations (e.g., at a zebra crossing)
- The **in-vehicle communication** between DART and passengers
- The **communication** between DART and **other road users** (i.e., cyclists and manually driven vehicles)
- **Way finding at transit hubs** when the new operation system is deployed since bus departure points may vary throughout the day
- The **provision of information** related to routing and schedules at bus stops

Since the aforementioned scenarios directly involve users of DART, a Human-Centred Design (HCD) approach is required, which foresees that innovation is based on focusing on the needs and wants of humans. Literature suggests that research in this field is sparse (Deb, Carruth, *et al.*, 2017). Therefore, additional research efforts are required in this field.

1.4 Work structure

Following chapter 1, in which the problem statement and the scope of the work is presented, chapter 2 presents the topics of design including the aspects of industrial design, design processes, and design methods. After a brief history of the developments of design towards its current understanding, a set of representative design processes is explained. Lastly, an overview of conventional design methods is given. This chapter provides a basic understanding of the profession of industrial design that is part of the investigation in the present dissertation as well as structures of design processes that represent ways of working as designers.

In chapter 3, the state of the art in terms of VR in the field of design is described. After providing definitions of terms and application fields of VR, the usage of the technology during activities such as problem identification, concept generation, evaluation and product presentation is elaborated.

Chapter 4 gives an overview of the stance of the thesis regarding three topics that were investigated before the conduct of the design studies. Firstly, it describes an analysis of a selection of validated design processes regarding their form, approaches, structures, and activities throughout the product development. From this investigation, a design process consensus model is derived that functions as a representative design process that is used in the present dissertation. Secondly, the transfer of conventional design methods into VR is described. This subchapter includes a presentation of factors that were relevant for the planned design studies consisting of the number of involved participants (i.e., users, lead-users, experts), the study scale (i.e., from a small study to a large-scale study), type of data (i.e., preferences, behaviours, expertise), as well as qualitative and quantitative data collection. Out of this elaboration, five design methods are chosen to be combined with VR. And thirdly, a literature research is conducted to derive a preliminary set of criteria for evaluating design studies. The insights from these investigations are necessary for structuring and understanding the subsequent chapters. Subsequently, based on a summary of problem statements the research gap is presented and research questions are defined for the following design studies.

Chapter 5 provides an overview of the used methodology, beginning with the description of expert interviews to validate and refine the previously derived set of evaluation criteria. Subsequently, the methodology for a benchmark study is explained that functions as a proof of concept that VR design methods can trigger authentic behaviours and reactions. The core of this chapter focuses on a framework to explain and evaluate each of the five design studies alongside the design process. Therefore, the framework for each design study contains three parts:

- **The development of the VR apparatus** including the description of used hardware, VR environment, manpower, and expertise.
- **Data collection and test of the method** including the description of study participants, data collection venue, data collection time, and effort.
- **Evaluation of the VR method** in which the newly developed VR design method is compared to two conventional design methods in consideration of the previously defined set of evaluation criteria.

Lastly, it is explained in chapter 5, how the VR method toolbox for industrial designers was developed.

In chapter 6, all results are presented, starting with the refined set of evaluation criteria based on the expert interviews. Subsequently, the findings of the benchmark study are shared. Subsequently, the chapter is divided into the five design studies. Similar to the preceding chapter, the findings throughout the development and data collection of each respective method are shared. Afterward, each VR design method is compared to two conventional design methods, one method of abstract nature and one method of tangible nature.

In chapter 7, the previously defined research questions are answered based on the conduct of the five design studies and the comparison of the applied VR design methods with conventional design methods.

Chapter 8 presents a toolbox for designers consisting of one introduction card and five method cards describing techniques in which VR is utilized within design methods. Furthermore, general design guidelines are presented in order to help develop and conduct design studies with VR.

Chapter 9 consists of a discussion setting the previously derived results into context to other researchers. In the first part, the case studies are discussed, followed by the discussion and reflection on the previously answered research questions. Thus, it will be elaborated how these investigations can draw conclusions regarding the implications of the impact of VR on industrial design. A high-level reflection will elaborate on the impact that the systematic usage of VR could have on design as profession. This chapter also contains the presentation of study limitations.

In chapter 10, a summary of the present dissertation is presented followed by a conclusion including aspects such as the answers of the research questions and connected implications. Lastly, an outlook for further investigations is shared.

2 Introduction to design, processes, and methods

In the following chapter, an introduction to design and industrial design is given, including a brief history and developments. Furthermore, a range of validated design processes is presented. Lastly, design methods and their utilizations during the design process are described.

2.1 Design – Tentatively defined

The term design originates from the Italian word “Disegno” (i.e., drawing). Since the renaissance, this term stands for a concept, a sketch, and the work of an underlying idea (Hauffe, 2008). Therefore, in the 16th century, the word design was used for expressing to have a plan of something that is intended to be realised, a graphic sketch of an artwork, and an object of applied arts (Bürdek, 2005; Hauffe, 2008). Cross (2008) states that everything that is not an untouched piece of nature is designed by someone.

“Design is to design a design to produce a design.” (Heskett, 2002).

This exaggeration from Heskett (2002) illustrates the challenge in defining the term design. Over the time, the term design and the definition of its objectives, goals, application fields, and focuses continuously changed (Hauffe, 2008). Hauffe (2008) and Hirsch (2014) point out that the blurry definition of design results out of the missing protection of the term. This leads to incorrect usage of the term design as well as a wrong understanding of its meaning since it is for instance misused to describe something as being “different” or “outstanding” (based on Hirsch, 2014). Heskett (2002) states that design has become something banal and inconsequential however, if it would be treated seriously, design could be an “anvil” for shaping the human environment for betterment and delight of all. Based on the Commision of the European Communities (2009), Götzendörfer (2014) concludes that there is no uniform definition of the term design. Therefore, as a first step, the term “design” will be tentatively defined by differentiating it from other fields, particularly the fields of art, manufacturing, and science (based on Archer, 1979; Heufler, 2004; Cross, 2006; Hauffe, 2008).

Aicher (1991) states that in contrast to art, design is for everybody, not exclusively for selected people or even individuals. Design wants to be reproduced and duplicated while reaching the biggest possible number of pieces and distribution. Aicher (1991) further states that design and art is not compatible by comparing the two fields like the relationship between “fire and water”. While design is measured by its underlying sense, functionality and its economy, art can be free of value, and free of sense.

The difference between design and manufacturing is that due to industrialization, the development of a product and its manufacturing was not directly interlinked anymore since a product could be produced industrially and thus, in large numbers while being developed independently and without involving the process of its crafting (Cross, 2008; Hauffe, 2008; Heufler, 2004).

The difference between design and science is multifaceted. Science tries to define problems as exactly as possible as hypotheses or even as numerical equations (Rittel and Webber, 1973; Rubin and Chisnell, 2008). Thus, these well-defined problems have a clear goal, mostly have just one correct answer and rules of proceeding to solve them (Cross, 2008). Rittel and Webber (1973) defined these problems as ‘tame’ problems. In contrast, designers are mostly dealing with ill-defined problems, so called ‘wicked’ problems (Rittel and Webber, 1973; Schön, 1983; Cross, 2006). Rittel and Webber (1973) defined the following rules for wicked problems:

- Wicked problems do not have a definitive formulation.
- There are no stopping rules for wicked problems.
- Solutions to wicked problems are not true or false, but good or bad.
- There is no immediate or ultimate test of a wicked problem’s solution.
- Every implemented solution to a wicked problem is consequential. Thus, every attempt to improve it counts significantly.
- Wicked problems do not have an exhaustive set of potential solutions and there is no well-defined set of operations that may be incorporated into the plan.
- Wicked problems are essentially unique.
- Wicked problems are symptoms of other problems.
- The discrepancy defined by a wicked problem can be described in numerous ways. The explanation determines the nature of the solution to the problem.
- The planner has no right to be wrong.

Based on Cross (1982), Willem (1990) states that the values of science are objectivity, neutrality, rationality, and a concern for truth. In contrast to that, values of design are ingenuity, empathy, practicality, and a concern for appropriateness. In this context, Grant (1979) stated: “Most opinion among design methodologists and among designers holds that the act of designing itself is not and will not ever be a scientific activity; that is, that designing is itself a non-scientific or a-scientific activity.”

To summarize the aforementioned aspects, the following characteristics can be attributed to design:

- Design is for everybody
- Design wants to be reproduced
- Design deals with wicked problems
- The values of design are ingenuity, empathy, practicality, and a concern for appropriateness
- Design aims to change a current situation into a better one

To further understand the term of design, a short excursion into the history of design is made.

2.2 Design – A brief history

Since design covers a multifaceted spectrum, in the present dissertation a brief overview of key changes throughout the time is given that led to our present understanding of the term. Design started when human beings first created tools and utensils by employing suitable materials and intentional functions (Heufler, 2004). Bürdek (2005) traces the origins of functionally optimized product design back to the classical antiquity. During that time, Vitruvius (ca. 80-10 B.C.) stated that there is a close relationship between theory and practice and that an architect must be interested in science, art, while being skilled in rhetoric, philosophy, and history. In his book, Vitruvius names the three principles "firmitas" (strength), "utilitas" (functionality), and "venustas" (beauty). There is the assumption that these three principles formed the basics of functionalism (Bürdek, 2005). However, the term design as it is understood today originated after the first industrial revolution. This led to changes such as mass production and new distribution methods. Social consequences of the industrial revolution became visible in the increasing poverty of large parts of the population.

During that time, reform movements originated to counteract the mass production, low-quality products, and pollution. One of these movements was called "arts and crafts" initiated by William Morris, John Ruskin, as well as several further architects and artists (Ruskin, 1900). The goal of this movement was to put an emphasis on manually produced products that incorporate aesthetics at the highest level while establishing aesthetics as a social criterion for proving that art, moral, and politics are inseparable (Bürdek, 2005; Chodzinski, 2007; Götzendörfer, 2014; Hauffe, 2008; Hirsch, 2014). By rejecting mass production, focusing on arts and crafts, and preference for simplicity, this movement influenced other movements such as the "art nuveau", "Jugendstil", the "Modern Style", the "secession Style" the "German Werkbund" as well as the "Bauhaus" (Bürdek, 2005). Therefore, the arts and crafts movement was part of laying down the foundation for today's profession of industrial design. Another movement caused by the industrialization was called functionalism.

In contrast to the arts and crafts movement, the functionalism did not reject mass production but had the intention to make industrial products better by adapting its requirements to the manufacturing process while offering moral and social-reformer aspects (Heufler, 2004; Hauffe, 2008). Therefore, this movement was led by the underlying aspiration: "form follows function", which means that a product's function is leading towards the shape and that there are no unnecessary decorations. Furthermore, the product language should follow the standards of industrialized manufacturing in order to produce high-quality and durable products to inexpensive prices (Hauffe, 2008).

The "German Werkbund", was a society of artists, industrialists, craftsmen, and journalists who had the goal to improve mass-produced products by uniting industries, craft trades, and arts in terms of public work and education (Bürdek, 2005). It was founded in 1907 in Munich, Germany. Lead members of the German Werkbund were Peter Behrens, Theodor Fischer, Herman Muthesius, Friedrich Naumann, Karl Ernst Osthaus, Bruno Paul, Richard Riemerschmid, Karl Schmidt, and Henry van de Velde (Bürdek, 2005; Hauffe, 2008). Peter Behrens, who was appointed as artistic advisor to "Allgemeine Elektrizitäts Gesellschaft" (AEG) is considered to be a pioneer for modern design (Bürdek, 2005; Hauffe, 2008; Heufler, 2004). His responsibilities were the design of factory buildings and electrical domestic products. Beyond that, the work of Peter Behrens initiated the emergence of corporate identity (Hauffe, 2008; Heufler, 2004). During that time, the Weissenhof project attempted to introduce a holistic design approach for designing a house starting from the walls of the house (architectural focus) and considered everything even up to the coffee cups in the cabinets. The idea of a holistic approach in design corresponded to the basic understanding of Bauhaus (Bürdek, 2005).

After the school of arts and crafts merged with the Academy of Arts in 1919 to form the "Staatliches Bauhaus Weimar", the Bauhaus became the centre for the subsequent design development, based on the idea of functionalism (Bürdek, 2005; Hauffe, 2008). The overall goal was to overcome the historicism through a clear design language and unity of arts, crafts, and industry. Walter Gropius, one of the initiators of the Bauhaus guided the idea that technology might be independent from art, but art needed technology. This laid the foundation of modern industrial design as it is understood nowadays.

2.3 Definition of industrial design

To further clarify the term design for the present dissertation, current subcategories of design will be further elaborated and the field of "industrial design" will be focused. Heufler (2004) distinguishes between five fields of design:

- Product design
- Transportation design
- Fashion design
- Environmental design
- Communication design

"Industrial Design is a strategic problem-solving process that drives innovation, builds business success, and leads to a better quality of life through innovative products, systems, services, and experiences." (World Design Organization, 2015). The term industrial designer refers to a practitioner of the intellectual profession, not only a trade of services for clients. Industrial design combines the design fields that are the closest to the industrial production technology. This means that considering the five fields of design described by Heufler (2004), industrial design incorporates product design and transportation design (Heufler, 2004; Papanek, 1984). Papanek (1984) states that the goal of industrial design is to achieve forms that 1) assure acceptance from all stakeholders before a capital investment is made and 2) can be manufactured at prices that allow wide distribution and reasonable profits. Industrial designers bring their services as companies' employees in own design departments, as employees of design offices, or as freelancers. Their activities comprise the planning and development of industrially manufactured products and goods while having a close interdisciplinary cooperation with other development teams (Heufler, 2004).

Frenkler (2020) defined in a formula that (industrial) design (d) is the space that the integrals of function, form and experience define in consideration of the following factors: Technology (Tech), Ergonomics (Erg), Sociology (Soc), Ecology (Eco), Psychology (Psych), Philosophy (Phil), and Finance (Fin) indexed by the brand's individuality, dependent from time (t) and in relation to presentations (Pres) in 4-, 3-, 2- and 1- dimensional expression (Figure 2).

$$d = \int_{function}\int_{form}\int_{experience} \frac{(T_{ech} E_{rg} S_{oc} E_{co} P_{sych} P_{hil} F_{in})^{brand}}{t} \times P_{resentation}^{4/3/2/1}$$

Figure 2. Design formula (Frenkler, 2020)

The equation demonstrates that industrial design goes beyond the point of designing products in consideration of functionality and aesthetics but is required to consider fundamental aspects beyond the shape regarding manufacturing, anthropology, and society (based on Frenkler, 2017).

Dieter Rams (2016), who is considered as one of the most influential industrial designers of the twentieth century, defined ten principles for design, stating that “good” design is innovative, makes a product useful and understandable, is aesthetic, and unobtrusive. Design further needs to be honest, long-lasting, thorough down to the last detail and environmentally friendly. With his last principle, Dieter Rams summarizes “good” design as “little design as possible” (Rams, 2016). Similar to the design formula of Frenkler (2020), the ten principles by Dieter Rams illustrate that good design goes far beyond aesthetics and looks, but involve crucial aspects such as the environment, sustainability, and our society.

Heufler (2004) defines a set of expectations that industries have on industrial designers that also involve factors defined by Frenkler (2020) and Rams (2016):

- Creativity considering the competency of problem-solving skills
- Identification and investigation of ergonomic problems
- Ability to draw plans and concepts
- Computer-aided three-dimensional design skills
- Knowledge from mechanical engineering to electrical engineering
- Knowledge of manufacturing processes
- Knowledge of economic thinking
- Capacity for teamwork and dedication
- Consciousness or cultural responsibility

In the present dissertation, the term industrial design is used with the meaning of the activity an industrial designer carries out to develop products out of an underlying problem statement, need, or idea. The result of the activity is supposed to fulfil user needs as well as needs for all involved stakeholders. To achieve this, the designer has to be aware of different aspects like technology, ergonomics, sociology, ecology, psychology, philosophy, and finance. All these aspects have to be considered in the context of development time and the intended application field.

2.4 Definition and structures of design processes

“Classifying design by its end product seems to be rather putting the cart before the horse, for the solution is something which is formed by the design process and has not existed in advance of it.” (Lawson, 2005). This quote by Bryan Lawson (2005) illustrates the importance of the design process for classifying design rather than its end product. Hence, in this chapter, beyond a definition of design processes involving a range of validated processes, the different structures and characteristics of these design processes are presented.

The design process describes stages, approaches, and activities designers absolve while designing products (based on Wynn and Clarkson, 2005). Cross (2008) reflects on the point where design is finished and the manufacturing can start. Since manufacturing cannot commence before the design is done, the goal of the design process is to describe the way of designing and to finally give a clear description of the artefact. In the same way as there are many definitions for the term design, there are also many opinions of how the design process is defined. Cross (2008) points out that there have been many attempts to visualize the design process in various ways for example by simply describing the sequences of performed activities (i.e., descriptive models), while other attempts try to prescribe activity patterns (i.e., prescriptive models). In a comparison of design processes based in different professions such as industrial design, mechanical engineering and transdisciplinary professions, Wynn and Clarkson (2005) categorized design processes into the categories of *approach* (i.e., whether the process model is stage- and/or activity-based), if the model is *solution- or problem-oriented*, and if it is *design- or project-focused*. Gericke and Blessing (2011) classify design process models by similar categories.

The following factors will be considered for defining and categorizing design processes (based on Wynn and Clarkson, 2005; Gericke and Blessing, 2011, 2012):

- The **type of support** investigates whether the examined methodology is a *process model*, a summary of *design methods*, a *combination* of both, or a summary of *management methods*.
- A **stage** is a subdivision of the design process, divided by the state of the product development. A process stage involves a considerable amount of time. Usually design processes cover three core stages: i) problem definition, ii) conceptual design, and iii) detail design.
- An **activity** is a subdivision of the design process that is based on the problem solving process. It involves a shorter period of time and it reoccurs several times throughout the process. Included activities are: i) generating, ii) evaluating, and iii) selecting.
- A **strategy** describes the sequence in which stages and activities are planned and executed through the design process, for example cyclic, stepwise, iterative, or decomposing. Process models could be either stage-based, activity-based, or a combination of both.
- The **orientation** can be divided into *solution oriented* (i.e., a solution is proposed, analysed, and iteratively modified) and *problem oriented* (i.e., concentrate on analyzing the problem, characterized by abstraction).
- The **focus** of the methodology can be categorized into *design focused* (i.e., emphasis on product design activities such as improvement of functionality) and *project focused* (i.e., emphasis on management activities such as product planning, marketing, and risk management).
- The **approaches** of the methodology can be categorized into *abstract* approaches which represents a high degree of abstraction in proceeding through the process, *analytical* approaches that represent, analyze and improve specific aspects of design projects, and *procedural* approaches which presents a more detailed level of abstraction including more specific aspects of the design process. *Procedural* approaches can further be categorized into *descriptive* approaches (i.e., by describing good practice of design) and *prescriptive* approaches (i.e., based on systematic sequences of design stages and activities, represent improved processes in terms of effectiveness and efficiency compared to non-systematic design processes).

A selection of validated design processes is presented as follows:

Design process model by John C. Jones (1963; based on Wynn and Clarkson, 2005) from 1963:

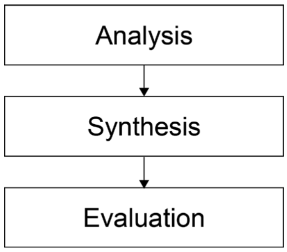


Figure 3. Design process by John C. Jones (1963)

The prescriptive model of the design process by Jones is divided into three main stages: analysis, synthesis, and evaluation (Cross, 2008). This process constitutes a problem-solving model. Wynn and Clarkson (2005) state in consideration of Jones' design process that problem-solving models usually are linear. The first stage consists of the problem consideration and structuring of objectives. The second stage involves the generation of solutions, whereas the last stage consists of the evaluation of the previously defined solution concepts in consideration of the objectives. As Figure 3 shows, the design process introduced follows a stepwise strategy.

Design process model by Bryan Lawson (2005) from 1980:

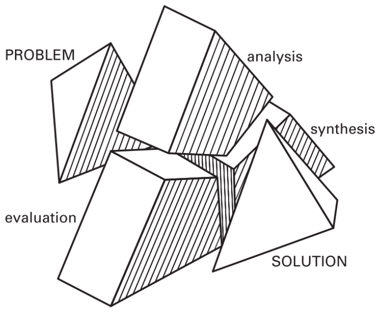


Figure 4. Design process model from Bryan Lawson (2005)

In his three-dimensional illustration of a design process model Lawson describes the three iterative activities of analysis, synthesis, and evaluation that are already known from Jones (1963). These activities are executed in order to derive a solution from an underlying problem. In contrast to the design process of Jones (1963), Lawson (2005) states that the activities are not executed in a linear way, but when they are needed (i.e., iterative nature). The activities offer as much help as designers need to navigate through the design process without the description of exact steps (Figure 4).

Design process model by Bruce Archer (Cross, 2008; Jones, 1984) from 1984:

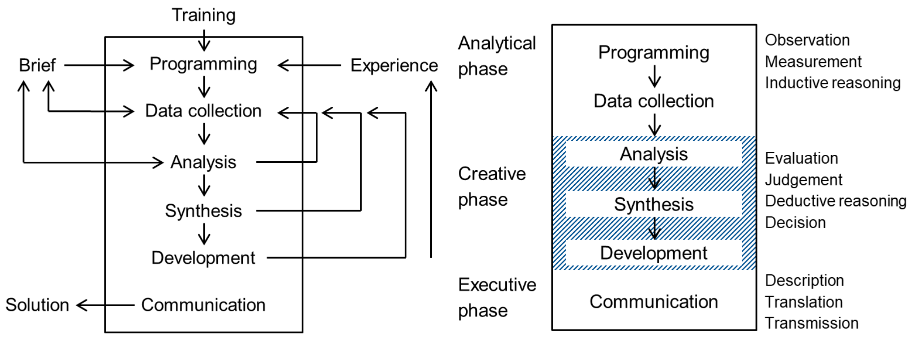


Figure 5. Design process by Bruce Archer (Jones, 1984)

The design process by Bruce Archer (based on Cross, 1984) is a more detailed prescriptive model than the process introduced by Jones (1963) since it also considers interactions outside the process, such as the training and experience of the designer, inputs from the client, and other sources of information (Cross, 2008) (Figure 5). Archer defined six types of activities that also include feedback loops (based on Cross, 2008):

- Programming: The definition of crucial issues and proposal of actions
- Data collection: The collection, classification, and storing of data
- Analysis: The identification of sub-problems and preparation of design specifications
- Synthesis: The preparation of design proposal outlines
- Development: The development of prototypes and the conduct of evaluation studies
- Communication: The preparation of the manufacturing documentation

Archer summarized his design process into three broad stages: Firstly, the analytical stage involves the observation of objectives and inductive reasoning. Secondly, the creative stage requires involvement, deductive reasoning, and subjective judgement. And thirdly, the executive stage includes the development of drawings and schedules. Even though the process model includes feedback loops, the process model of Archer is considered to follow a step-wise strategy.

Design process model by Michael French (1985; Cross, 2008) from 1985:

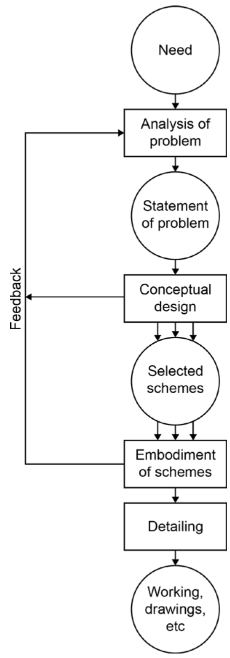


Figure 6. Design process by Michael French (1985)

French proposes a detailed descriptive design process model that involves four activities that are represented as rectangles as well as four inputs/outputs that are represented by circles. After an initial statement of a need, the underlying problem is analysed. This leads to a problem statement which builds the basis for the conceptual design in which rough solutions are generated in consideration of practical knowledge, production methods, and commercial aspects.

French (1985) states that this stage demands the designer the most. As a result of this stage, schemes are developed and selected. In the next stage, the schemes are refined and a final choice for one solution scheme is made. This includes a high involvement of feedback loops to the conceptual design stage. Still, as Figure 6 shows the design process by French (1985) follows a step-wise strategy. In the last stage, details are defined and developed. The final output is the description of the artefact via technical- and computer-generated drawings.

Design process model by Nigel Cross (2008) from 1994:

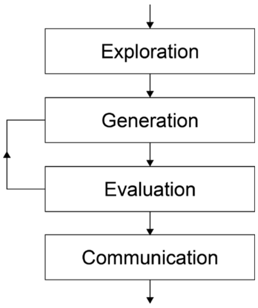


Figure 7. Design process by Nigel Cross (2008)

In his descriptive model of a design process, Cross (2008) proposes four stages in which designers first explore problem spaces before starting the concept generation (Figure 7). These concepts are then iteratively evaluated in consideration of the objectives, criteria and the design brief. As a final step, the communication between the designer and manufacturer happens. The design process of Cross (2008) follows a step-wise strategy.

Design process model by Gerhard Heufler (2004) from 2004:

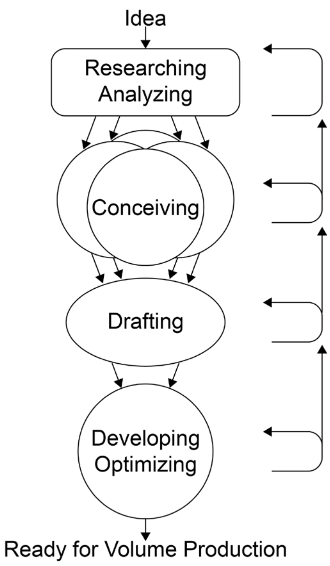


Figure 8. Design process by Gerhard Heufler (2004)

Heufler (2004) proposes a design process consisting of four iterative stages (i.e., stage-based strategy). In the first stage, the *Researching and Analysing*, tasks are set based on a basic idea or problem scope. Furthermore, relevant information is gathered, target groups are defined and a briefing is developed. The goal of the first stage is the problem identification. In the second stage, the *Conceiving*, basic solution approaches and variants are created. In the subsequent *Drafting* stage, CAD models and prototypes are created. The goal of this stage is to define a solution for the previously defined problem. In the last stage, the *Developing and Optimizing*, details are worked out, the overall design is optimized and the implementation is ultimately approved before the product is ready for volume production (Figure 8). The arrows shown in the process model demonstrate that divergent thinking happens from stage one to stage two, whereas from stage two onwards, convergent thinking is used to focus on the solution approach and to define the final product. Additionally, Heufler (2004) provides a larger framework of product development that illustrates the interdisciplinary character of design (see Figure 9).

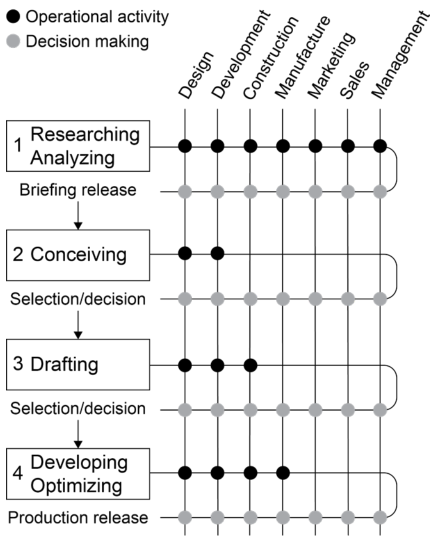


Figure 9. Design as an interdisciplinary process (Heufler, 2004)

Heufler (2004) states that design always must be considered in the larger framework of the whole product development, including other departments such as development, construction, manufacture, marketing, sales, and management. Therefore, design has an interdisciplinary team character. Figure 9 shows that design is involved in every operational activity as well as in every decision making. Even though every other department is involved in the decision making, their contribution as operational activity during the different stages of the design process varies.

Design process model by Sandra Hirsch (2014) from 2004:

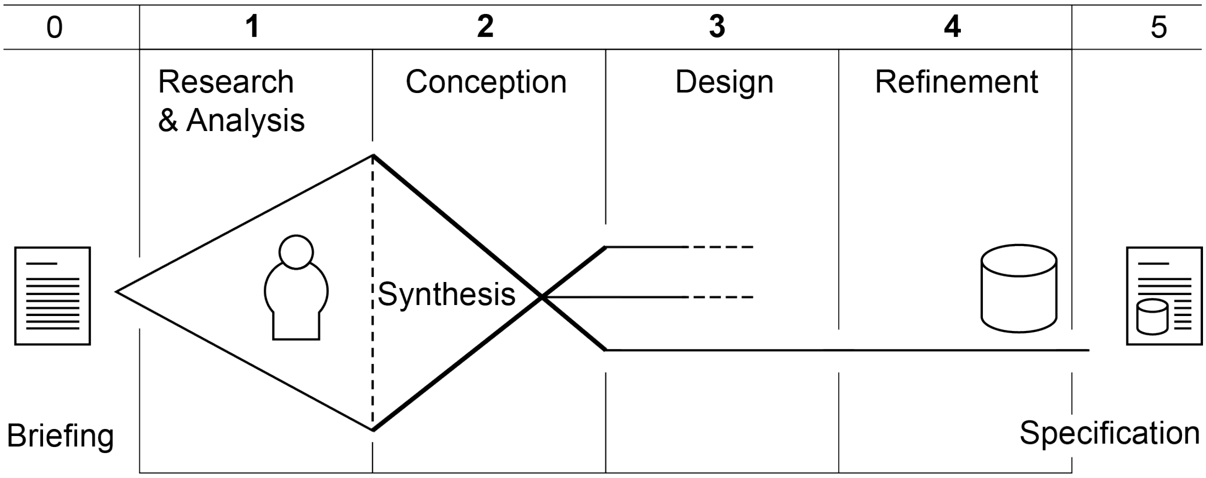


Figure 10. Design process by Sandra Hirsch (2014)

Hirsch (2014) proposes a design process that consists of four core stages, showing similarities to Heufler's design process (Figure 10). In the first stage, information is gathered and contexts are established. In the second stage, the previously gathered information and experiences are clustered and put into relation to one another. This stage also includes the synthesis[2]. At the end of the *Conception,* a range of rough solution approaches is developed and presented to the clients or internal decision makers. In the third stage, the concept alternatives are elaborated and analysed with stakeholders of the product development. In this stage, drawings, sketches, CAD models, and function prototypes are developed. The last stage contains the development of shape- and design- prototypes considering the previously defined requirements such as feasibility, material, colour, and surface treating. Furthermore, during this stage, user evaluations are conducted. Lastly, a design specification for the final product is created. Additionally, Hirsch's design process model illustrates stage 0, in which the briefing and vision is defined, and stage 5 in which the entrepreneurial implementation is conducted. However, since these activities contain design- and innovation- management activities, they are not considered as part of the core stages of the design process. The present design process follows a stage-based strategy.

[2] With the help of a synthesis, the gathered information is clustered, rearranged, questioned, and reassembled into new prospects (Hirsch, 2014).

Double Diamond by the British Design Council (2020):

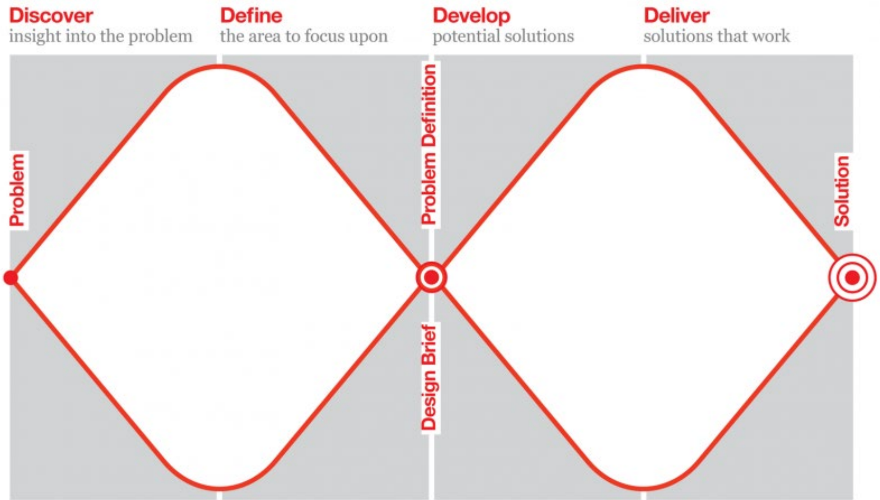


Figure 11. Double Diamond by the British Design Council (2020)

The Double Diamond design process introduced by the British Design Council (2020) defines a process involving a stage-based strategy consisting of the four stages *discover*, *define*, *develop*, and *deliver (*Figure 11). The name is derived by the visualization of convergent and divergent thinking throughout the process which is displayed as two consecutive diamonds. While in the first two stages, divergent and convergent thinking is applied to define the right problem, the same approach is applied in the third and fourth stage to find the right solution. Designers have the following objectives throughout the stages (based on British Design Council, 2020):

- **Discover:** The process is started by questioning the challenge(s) which leads to the identification of user needs
- **Define:** Understand findings as well as how the problem(s) and user needs are aligned results in a design brief that clearly defines the challenge(s) based on the gathered insights
- **Develop:** Develop, test, and refine multiple potential solutions
- **Deliver:** Select a single solution and prepare it for launch

As the presentation of different design process models shows, the “right” design process does not exist. Therefore, in the present dissertation, an attempt is made to derive a consensus model of the design process. This attempt is based on a framework that allows the investigation of a range of validated design processes to find a representative process model that incorporates the majority of characteristics of the investigated process models (i.e., 4.1 A consensus model for the design process).

2.5 Design methods

Design methods are techniques for aiding creative thought to carry out design practice throughout each stage of the design process (Cross, 2008; Jones, 1981; Kolko, 2011; Kumar, 2012; Martin and Hanington, 2012; Tjalve, 2015; Zwicky, 1967). Martin and Hanington (2012) state that design methods have the power to provide an opportunity to structure conversations that help to better understand and emphasize with people and thus build more meaningful products. The selection and usage of design methods are dependent on factors such as the scope of the project, budget, available manpower, but also the designers' personal preferences (Flick, 2014). Furthermore, it is dependent on the designer's convictions, beliefs, interests, but also the aim of the study, epistemological norms of the designers' practice, and previous work in the application context (Opoku et al., 2016). Thus, beyond the logical decision making, intuition and preferences from the designers are fundamental aspects when choosing design methods. Sekaran and Bougie (2016) state that the usage of data collection methods is dependent on the research strategy (e.g., experiments, survey, case studies), the researchers' interference in the study, the study setting (i.e., location), the data analysis (i.e., quantitative, qualitative, or mixed methods), as well as temporal aspects (i.e., the time horizon). Flick (2014) proposes a framework for deriving a concrete research design by considering aspects such as the goal of the study, research questions, methodological procedures, as well as temporal-, personal-, and material- resources available.

While there are "traditional" design methods that are used already since decades such as concept sketching to concretise, understand, and communicate ideas (Cross, 1999; Kumar, 2012; Martin and Hanington, 2012), designers also utilize methods from other disciplines such as ergonomic analyses in which usability is evaluated in consideration of factors such as anthropology, reachability, comfort, and safety (Martin and Hanington, 2012; Rubin and Chisnell, 2008). Jones (1984) states in his attempt to unify intuitive design methods with analytical or mathematical methods in "systematic design" that design methods have two effects: Firstly, a design method is supposed to reduce the amount of design errors, re-designs, and delay. And secondly, a design method is supposed to generate more imaginative and advanced designs. Jones (1984) defined a set of characteristics for design methods in his approach of "systematic design".

The design method should:

- Enable the designer to produce ideas and solutions at any time without being biased by practical limitations and analyses
- Provide a system for noting every item of design information, keep design requirements and solutions separate from each other, and provide a tool to relate solutions to requirements with as little compromise as possible

Considering the second aspect, Jones (1984) brings up the design process that he developed (see chapter 2.3 Definition and structures of design processes) and claims that during the stage of *Analysis*, design methods should help to list requirements, during the *Synthesis*, solution approaches should be elaborated thanks to design methods, and lastly, during the *Evaluation*, defined designs should be evaluated thanks to design methods in consideration of requirements, manufacturing, and sales.

There are countless design methods that can be utilized during different stages of the design process with various objectives. During early design phases, especially for the identification of problems, methods such as questionnaires, interviews, brainstorming, user journey maps, SWOT analyses, or competitive analyses can be conducted (van Boeijen et al., 2014; Gerstbach, 2017; Kumar, 2012; Martin and Hanington, 2012). During creative design stages of projects, methods such as sketching, CAD development, morphological analysis, paper prototyping, or concept brainstorms are conducted (Eissen and Steur, 2011; Gerstbach, 2017; Kumar, 2012; Martin and Hanington, 2012; Zwicky, 1967). For evaluative stages of the design process, methods such as usability testings, experience simulations, cognitive walkthroughs, ergonomic analyses or Wizard-of-Oz studies are conducted (Kumar, 2012; Martin and Hanington, 2012; van Boeijen, Daalhuizen and van der Schoor, 2014; Gerstbach, 2017). Methods can also be applied in several stages of the design processes and thus are not necessarily interlinked with one single design process stage. The method of heuristic evaluation for instance can be applied in early design stages for problem identification. Additionally, it can be applied in evaluative stages in order to evaluate design concepts (Martin and Hanington, 2012).

Sanders and Stappers (2012) state that the choice for appropriate design methods can be classified by criteria, the type of data they deliver, the level of academic rigor, training, or financial investment. The researchers provide examples in which projects and their research designs are defined including aspects such as budget, timeframe, stakeholders, and research objectives. One case study is mentioned by Sanders and Stappers (2012) in which five international students participate in a design workshop and decide to use interview toolkits and collages for data collection in the scope of travelling since this method could be developed, deployed, and analysed within one week and no budget is required (Sanders and Stappers, 2012). In contrast, Sanders and Stappers (2012) mention another case study in the field of "Family Leisure Time" including a budget of $500.000, a time frame of four months, and the involvement of four to six full-time employees. The project (that was a successful grant application) included stages such as literature research, preliminary fieldwork in four countries, analysis of collected preliminary data, generative design workshops in the four countries, full data analysis, a participatory event to identify additional opportunities and challenges, as well as a written report. By comparing these two case studies, it becomes evident that beyond a research objective, the project setting including available budget, time, and capacities are crucial aspects for deciding for an appropriate research methodology. While questionnaires for instance is a design method with advantages in terms of time and cost, it could lack in validity. In contrast, prototyping usually involves more time and cost, however, concept evaluations by using prototypes usually ensure valid data collections. Nevertheless, due to the accelerated product development processes and shortened product life cycles, products need to be developed in a shorter period of time and with a decrease in cost to allow industries to remain competitive. Hence, by applying conventional design methods it becomes increasingly more difficult for industrial designers to meet the requirements of all stakeholders while still designing a product that has the potential to be implemented on the market successfully (Jones, 1981).

Technological advances already impacted the profession of industrial design and its design methods, such as the introduction of Computer-Aided Design (CAD). The introduction of CAD to the design process led to more efficiency in terms of time spent and costs during the development of products while increasing the accuracy for modelling prototypes and defining product specifications (Akca, 2017; Boothroyd, 1994; Tovey, 1989). The current trend in using extended realities such as VR also in industries also raises the question for instance how this technology could be incorporated in the profession of industrial design and how it could be useful in this context. Therefore, in the following chapter, an overview of the application of VR during the different stages of the design process and its utilization for design methods is provided.

3 State of the art – Virtual Reality in design

3.1 Introduction to Virtual Reality

The majority of definitions for VR have a consensus of understanding. Oxford English Dictionaries (2018) defines VR as “the computer-generated simulation of a three-dimensional image or environment that can be interacted with in a seemingly real or physical way by a person using special electronic equipment, such as a helmet with a screen inside or gloves fitted with sensors.” The Cambridge Dictionary (2014) defines VR as “a set of images and sounds, produced by a computer, that seem to represent a place or a situation that a person can take part in”. Gigante (1993) writes: “VR is characterized by […] the illusion of participation in a synthetic environment rather than external observation of such an environment. VR relies on three-dimensional (3D), stereoscopic, head- tracked displays, hand/body tracking and binaural sound. VR is an immersive, multi- sensory experience.” Mihelj, Novak and Beguš (2013) define VR as an interactive computer simulation that augments the user’s state in a way so that the user gets immersed in a virtual environment.

It becomes evident that the definitions include the aspect of a simulation (i.e., image, sound), electronic equipment (such as computers and displays), and an environment (i.e., a place or a situation). However, the definitions do not agree upon a certain technology that enables the experience, nor the aspect of immersion.

The definition of VR underlying the work is as follows “A computer-generated simulation that can be interacted with, consisting of images, videos, and/or sound that represents an environment that the viewer can experience by using electronic equipment”.

The term Extended Realities (XR) refers to all real-and-virtual combined environments generated by computer technology and wearables (based on Fast-Berglund, Gong and Li, 2018). Beyond VR, this also includes Augmented Reality (AR), and Mixed Reality (MR) (Jerald, 2016). While AR refers to technology that augments the visual field of the user with information (Caudell and Mizell, 1992), MR is defined as a mixture between real and virtual world in which virtual content augments the reality and vice versa (Barfield, 2015). Figure 12 shows the relation between the different technologies from a physical system to a virtual system.

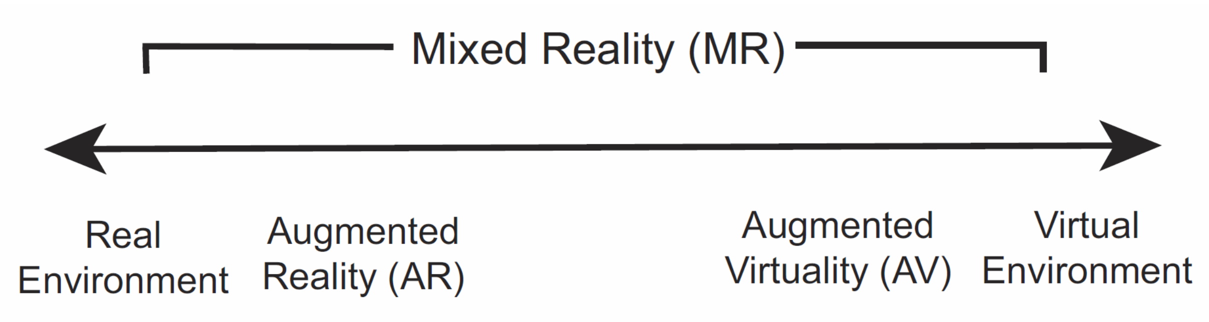


Figure 12. Relation of Extended Realities (Milgram and Kishimo, 1994)

Key terminology of VR includes:

- **Virtual environment:** A description of virtual objects within a simulation including the rules and relationships to control them (Mihelj et al., 2013)
- **Presence:** A subjective experience of being in an environment or place, even when being physically situated in another place (Witmer and Singer, 1998)
- **Immersion:** "[…] a psychological state characterized by perceiving oneself to be enveloped by, included in, and interacting with an environment that provides a continuous stream of stimuli and experiences." (Witmer and Singer, 1998). Thus, presence is dependent on immersion. The greater the sense of immersion, the higher the level of presence
- **Interactivity:** The possibility to affect virtual environments and/or change the angle and location from which the user can view this virtual environment (Mihelj et al., 2013)
- **Head-Mounted Display (HMD):** A display that can be equipped on the head in front of the eyes of a user and shows perspective images that move as the user moves (Sutherland, 1968)
- **CAVE:** CAVE – Automatic Virtual Environment refers to a room in which virtual content is projected on the wall(s), floor, and/or ceiling to generate an immersive virtual experience (Cruz-Neira et al., 1992)
- **Degrees of Freedom (DoF):** DoF describes the freedom of movement of a rigid body in a three-dimensional space (Batallé, 2013; Paul, 1981). In the field of VR, 3 DoF refers to possible head-movements (i.e., up and down, right and left), whereas 6 DoF additionally refers to positional movements (i.e., forward and backward)

The very first concrete idea of VR was described in 1962 by Morton Leonard Heilig who presented the first virtual simulator, called "Sensorama" (Heilig, 1962). Sensorama aimed to simulate all senses by allowing its user to see a three-dimensional city, hear ambient sounds, feel wind, and smell certain scents. Thus, users could take a motorcycle ride through New York. The Sensorama simulator however was not interactive which means that the motorcycle route was pre-recorded (Gigante, 1993). Figure 13 shows the Sensorama simulator.

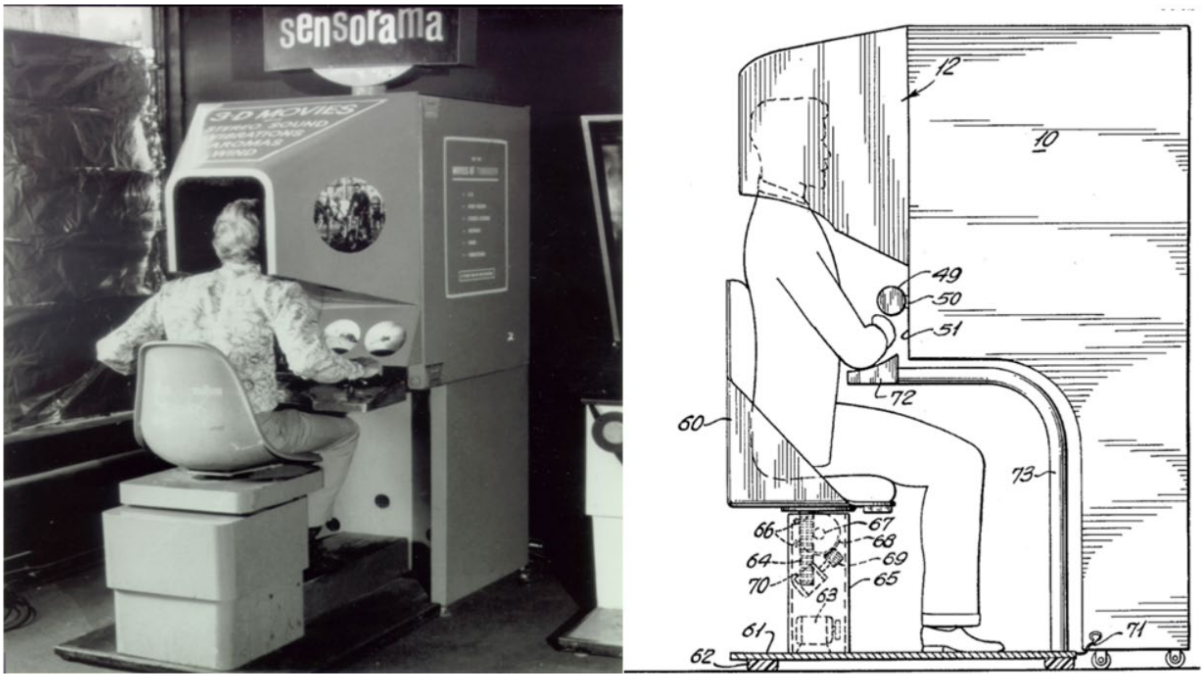


Figure 13. Sensorama (Heilig, 1962)

In 1965, Ivan Sutherland (1965) described an “ultimate” display that consisted of a room in which the computer controls the existence of matter (including sound, taste, and smell) including graphics and force-feedback devices. Three years later, Sutherland (1968) proposed what is considered the first HMD, called the “Sword of Damocles”. It included head tracking that correctly updated the stereo view dependent on the head’s position by using a pair of half-silvered mirrors (Batallé, 2013; Gigante, 1993; Mihelj et al., 2013). Figure 14 shows the Sword of Damocles, an HMD that was attached to the ceiling.

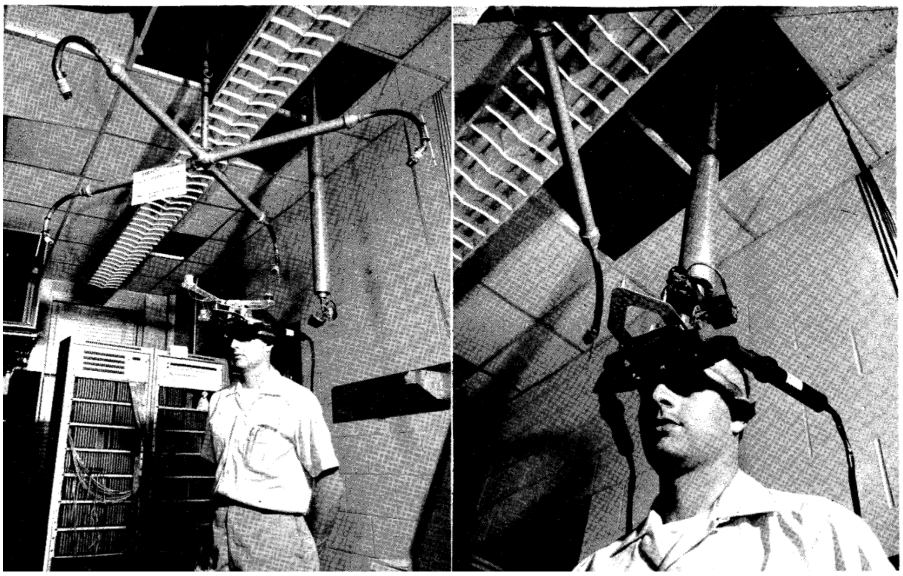


Figure 14. Sword of Damocles (Sutherland, 1968)

Since then, research is quickly progressing, especially in the military field for flight simulators (e.g., Tom Furness developed a fighter cockpit), aerospace (e.g., NASA developed a multi-sensory simulator and telepresence device), and other research fields such as informatics media labs, entertainment research, and science-fiction authors (Gigante, 1993; Mihelj et al., 2013).

The technology of VR is not a newly emerging technology but as it was pointed out its development already began in the 1960s. However, the accessibility to VR changed due to research and development. VR devices are becoming increasingly cheaper which retrospectively supports the creation of a mass market for this technology (Barnes, 2016).

Current and near future main markets for VR are forecasted to be gaming industry, entertainment, life events, wellness, and tourism (Reuters, 2017). Beyond that, VR is applied in industrial fields as well such as construction, military, and aviation (Berg and Vance, 2016; Mihelj et al., 2013). In the automotive industry, for instance, VR is used among others for marketing, visualizing, driving simulation, design reviews, and ergonomic studies. One example for a marketing application is the “AUDI VR experience” that lets potential customers experience vehicles with any available specification and configuration with the help of HMDs as shown in Figure 15 (Audi, 2017).

Figure 15. Audi VR experience (Audi, 2015)

In market research, VR has been used to investigate shopping experiences in malls (Lee and Chung, 2008) and product testings in VR (Mujber et al., 2004). Furthermore, VR is used in psychological studies due to its capabilities to create controlled and safe environments (Loomis et al., 1999). This includes case studies of extreme nature such as the investigation of human behaviour in fire escape scenarios (Wei, 2011) or the observation and treatment of test participants with acrophobia (Krijn et al., 2004). In the subsequent subchapters, the state of the art of using VR in design studies are presented.

One key aspect for interacting with VR environments are locomotion techniques that allow users to move inside virtual environments. Even though moving in VR is not mandatory for a successful experience, locomotion techniques has the potential to increase immersion as well as expands the experience for the users due to the larger world users can “walk” through (based on Witmer and Singer, 1998) .

There are various ways for traveling in VR, the most common and most used locomotion techniques are as follows (based on Weber, 2011; Mihelj, Novak and Beguš, 2013; Jerald, 2016; Boletsis, 2017):

- **Phsysical walking:** walking in the tracked area that is matched with the motion in VR
- **Redirected walking:** the space in VR is larger than the physical space to walk
- **Walking in place:** conducting physical walking motions while staying in the same spot
- **Arm swing:** swinging arms while ramaining stationary while the arm movements are translated into walking movements in VR
- **Treadmill walking:** using a treadmill to simulate the physical act of walking
- **Touchpad movement:** using the touchpad of the input device to move
- **Teleportation:** aiming at a certain point and teleport there by pressing/releasing a button
- **Human Joystick:** leaning towards a direction such as forward, backward, left, and right as well as turning during forward motion
- **Head-directed walking:** head movements control the movement's direction
- **Chair-based locomotion:** turning on a turning chair is translated into walking directions

The purpose of the expected VR experience as well as the skill level of users need to be considered in order to choose suitable locomotion techniques. While techniques that include phyiscal movements such as physical walking and arm-swing movement are especially well suited to experience the physical effort of moving and covering distances in VR, other techniques such as the touchpad movement and teleportation are efficient ways experiencing virtual environments.

As it was presented before, VR is already implemented in a range of different industries such as entertainment, construction, engineering, and automotive, resulting in advantages such as increased efficiency in terms of time and cost and increased engagement. Nevertheless, its utilization for design is still relatively sparse and its capabilities for industrial designers remain uncertain. Thus, in order to understand how VR can be a relevant tool for industrial designers, an overview of successful usages of VR along core activities during the design process is given in the subsequent chapters. This includes the utilization of VR for problem identification, participatory design, prototyping, concept evaluation, and presentation.

3.2 VR for problem identification

For the identification of problems of digital of physical products researchers use methods such as heuristic evaluation, usability testing, cognitive walkthrough, and the definition of guidelines. Considering digital products, these methods are mostly applied via desktop-based computer simulations (Jeffries et al., 1991; Marsh, 1999; Martin and Hanington, 2012; Nielsen, 1992; Sutcliffe and Gault, 2004). Experts experience products or applications in a controlled environment (e.g., a laboratory) and share insights, observations, and improvements based on their experience. This procedure is usually conducted either individually or small groups (Nielsen and Molich, 1990). Expert evaluation methods differ in involvement of participants, cost and benefit, as well as effectiveness for identifying minor and severe usability flaws (Mankoff et al., 2003). While methods such as applying guidelines rely on written instructions for developers while creating applications or products, other methods such as heuristic evaluation rely on a set of rules (i.e., heuristics) in order to evaluate usability (Jeffries et al., 1991). In cognitive walkthroughs, lead-users, experts, and developers use applications while trying to accomplish objectives. During the usage, usability flaws become apparent (Lewis et al., 1990; Polson et al., 1992; Sauro, 2011).

Product evaluations for identifying problems in VR are sparse. Carlsson and Sonesson (2017) conducted a user experience (UX) study in VR in which participants (i.e., lead users and experts) experienced cockpit UIs inside a vehicle. The results show that VR offered great opportunities for creating engaging and immersive experiences. The researchers defined a set of guidelines for the development of a VR simulator for UX that include aspects such as the usage of suitable narratives, ensure sensory congruence, and enabling a range of concepts to be tested. In this study, VR turned out to be a valid, cost-effective, and flexible alternative that allowed the conduct of evaluation tests in laboratorial environments.

Additionally, there is a range of studies that use experts' evaluation and especially heuristic evaluation for investigating VR applications (Gabbard et al., 1999; Murtza et al., 2017; Sutcliffe and Gault, 2004; Wang et al., 2019). Sutcliffe and Gault (2004) evaluated UIs of VR applications based on a set of adapted heuristics. Similarly, Gabbard et al. (1999) proposed an iterative HCD approach including heuristic evaluation of virtual environments. Silvennoinen and Kuparinen (2009) conducted a usability study (i.e., heuristic usability analysis) of medical simulators in VR. The researchers conclude that the simulator could constitute a promising tool for learning and training, concluding that user-friendliness is a key aspect for the simulator's efficiency. Nevertheless, all existing studies using forms of experts' evaluations focus on evaluating UIs for VR rather than using VR for conducting evaluations of UIs that are not intended for VR but for real application fields. Especially for this context, it remains open which impact the aspect of immersion could have to contribute to a more accurate evaluation and how the usage of VR could impact aspects such as capacities, validity of results, and effort for developers and experts.

3.3 VR for participatory design

Current approaches in design, such as the creation of meaning and value, are shifting from company-centred to user-centred approaches (Prahalad and Ramaswamy, 2004). Thus, designers progressively involve people into the design process to create shared value. This involvement leads to an improved identification of people's needs and wants and has the potential to increase the efficiency of the development of products while creating relationships with people (Prahalad and Ramaswamy, 2004). Participatory practices include approaches such as participatory design, co-design, and co-creation (Sanders and Stappers, 2008, 2012). A whole landscape of participatory design methods exists including techniques such as paper prototyping, collages, interviews, card sorting, and questionnaires (Bartl et al., 2010; O'Haire et al., 2011; Sanders et al., 2010). While these methods show great benefits such the capability to establish dialogues, facilitate collaborations, they also show limitations such as a high involvement of time and cost a lack of comprehensibility for hypothetical studies and low motivation for participation (Bann, 2002; Murphy et al., 2003; O'Haire et al., 2011). Farooq et al. (2018) conducted a study to collect people's preferences in VR in the field of pedestrian research, concluding that VR has the potential to improve the collection of people's preferences based on immersive experiences. Farooq et al. (2018) further points out limitations such as a great amount of effort for developing such a tool and requiring a considerable amount of expertise for the development.

The usage of VR in participatory design can also be challenging due to the uncertainty to which extent the technology is suitable for people of different heritage, age, prior knowledge regarding VR, or societies with varying access to and perception of technology in general (Pick and Azari, 2009; Stadler, Cornet and Frenkler, 2019b; Venkatesh and Morris, 2000). O'Brien et al. (2012) discuss experiences of technologies considering age and prior knowledge and conclude that designers need to understand the targeted user group's prior knowledge with technology to successfully facilitate its usage for participants. Gregor and Newell (2001) state that seniors have different capabilities in terms of sensory, physical, and cognitive functionality compared to younger people indicating that seniors have different needs than children, especially in terms of accessibility to technology. In summary, the advantages of using VR for conducting participatory design remains uncertain especially regarding its practicability, accessibility, and ease of use for certain groups of users.

3.4 VR for prototyping

Industrial designers usually use desktop-based CAD applications for prototyping such as Rhinoceros (2019) and 3ds Max (Autodesk, 2019). Commercial VR applications for CAD are already available, such as Gravity Sketch (Gravity Sketch, 2017), Microsoft Maquette (Microsoft, 2019) Google Blocks (Google, 2017), Mindesk (Mindesk, 2019), and flyingshapes (Flyingshapes, 2019). Nevertheless, it has to be clarified to which extent VR impacts CAD developments in terms of quality of outcome and time. Furthermore, the tools of these commercial VR applications for creating and transforming volume models and surfaces as well as the user interface and navigation vary. Additionally, functionality and usability of these applications and thus their suitability specifically for industrial designers has yet to be investigated.

Researchers already investigated the usage of VR in creative activities such as brainstorming, sketching, and CAD especially in the early stages of the design process, resulting in insights regarding the concept quality, impact on time and costs, and impact on decision making (Tovey, 1989; Boothroyd, 1994; Wendrich, 2010; Berg and Vance, 2016; (Tovey, 1989; Boothroyd, 1994; Akca, 2017; Deb, Carruth, *et al.*, 2017; Freeman, Salmon and Coburn, 2017). In contrast, the usage of VR in the later stages of the design process revealed limitations such as technical drawbacks like absence of haptic feedback (Bishop et al., 2001) and a restricted field of view (Berg and Vance, 2016). Even though the impact of VR on prototyping for industrial designers remains uncertain, it is expected that key characteristics of VR, such as the potential to experience products in real scale and directly in the (simulated) application field could be highly beneficial for product developments, and thus, for industrial designers.

3.5 VR for concept evaluation

There is a range of methods to evaluate design concepts, including usability testing, experience simulation, Wizard-of-Oz studies, SWOT analyses, or observations (van Boeijen et al., 2014; Kumar, 2012; Martin and Hanington, 2012).

In the field of pedestrian research for autonomous vehicles, a range of researchers conducted evaluation experiments for implicit and explicit communication concepts. Deb, Strawderman, et al. (2017) developed a pedestrian receptivity questionnaire that included items based on trust, attitude, system effectiveness, and social norms. The authors stated that a limitation of the study was the fact that the results were solely based on participants' responses and not actual behaviours. The authors anticipated that in consideration of the responses the actual behaviours could have differed when interacting with AVs (Deb, Strawderman, et al., 2017). This shows an important limitation of exclusively using questionnaires for concept evaluations in this specific context. It is anticipated that one missing key aspect is the lack of users' imagination and experience when answering questions for future scenarios (see chapter 4.3 VR for immersive large-scale surveys).

Using the method of Wizard-of-Oz means that participants can experience a system that appears real and functioning while the researchers perform behind the scenes to create this simulation, even though the system is not fully working yet (Dahlbäck, Jönsson and Ahrenberg, 1993; Martin and Hanington, 2012). This method has been used by several researchers to investigate actual participants' behaviours when being confronted with a transport system that appears to be automated (Clamann et al., 2015; Dey and Terken, 2017; Lagström and Lundgren, 2015; Mahadevan, 2018; Matthews et al., 2017; Rothenbücher et al., 2016). Clamann, Aubert and Cummings (2015) conducted a study in which participants interacted with an AV that was a disguised manually driven vehicle in an ambiguous situation. One limitation of the conducted experiment was the lack of safety. Studies show that main safety concerns in the field of pedestrian research are speed of the approaching car as well as the predictability of pedestrians' behaviours. Here, both aspects are interlinked and dependent from one another (Šucha, 2014). Thus, even if the vehicle is behaving correctly, there still could be potential safety hazards for pedestrians. In the aforementioned study, implicit and explicit cues of approaching vehicles were altered by the researchers. This implies that even if the vehicle would have behaved correctly, it may have led to inappropriate behaviours from the participants.

VR has been used in pedestrian research in order to ensure safety while causing authentic behaviours from participants. Several VR tools have been utilized in this context, including equipment such as HMDs, *CAVE* systems, or immersive video simulations (Dörner et al., 2013; Mihelj et al., 2013). VR has already been utilized to investigate behaviours related to the communication between pedestrians and vehicles (Morrongiello *et al.*, 2015; Chang *et al.*, 2017; Pillai, 2017; Deb, Strawderman and Carruth, 2018). Pillai (2017) conducted a study in which participants faced an approaching AV in an ambiguous situation (i.e., zebra crossing). The study focused on implicit communication such as gap distance from AV to pedestrian, human-like driving behaviour, and deceleration speed. Deb, Carruth, et al. (2017) developed a VR simulator in which participants were confronted with manually driven vehicles that ignored a traffic signal.

Nevertheless, limitations exist for design methods that involve the usage of VR, including resolution of displays, restricted field of view, and realism of the virtual environment. Therefore, research is still processing to accurately represent real-life scenarios within virtual environments while providing a suitable test-bed for pedestrian research (Deb, Carruth, et al., 2017).

3.6 XR for presentations

A range of studies utilized XR technologies for communication and presentation purposes. Erath et al. (2017) utilized VR for communication and research in the domain of transportation research in Singapore. The technology of VR was used for data collection (i.e., surveys) and communication to stakeholders. Zarraonandia et al. (2014) used AR as a tool for requesting and collecting user feedback from the audience, however, the researchers did not use the technology as actual presentation tool but as a feedback tool for presenters. Walczak & Wojciechowski (2006) investigated a platform for MR presentations including automated templates that can be utilized by stakeholders. Nevertheless, the researchers did not state its usability and acceptance of stakeholders. Koleva et al. (2001) created a space for MR presentations involving a physical presenter and compared it to virtual environments involving avatars.

The researchers raise issues regarding the usage of MR for presentation techniques, such as (based on Koleva et al., 2001):

- An introduction of participants gives the opportunity to get to know one another and to create a sense of space.
- The layout of the space impacts the mutual awareness of participants.

Nevertheless, the researchers did not compare the MR presentation technique to conventional presentation techniques but to a virtual setup. In conclusion, the usage of MR for product presentations and its impact on usability and user acceptance needs to be further investigated to derive its potential for industrial designers.

As it became evident, VR is already used in a range of studies involving key activities and techniques that designers already utilize. However, it needs to be investigated how VR can be integrated in each stage of the design process to assess its capabilities for industrial designers. To allow this, in the following chapter a consensus model of the design process is defined followed by explaining the methodology for combining conventional design methods with VR. Furthermore, a preliminary set of evaluation criteria is presented based on a literature review to allow a subsequent evaluation of the newly developed immersive design methods.

4 Stance of the thesis

4.1 A consensus model for the design process

Since there is no standardized design process, an investigation was conducted in order to develop a representative design process model that is used as a basis for the present dissertation. “A consensus can be found that at least on an abstract level design process models have a generic core of common stages. On a detailed level the picture is different. The extent to which design approaches appear similar depends on the perspective of the analyses” (Gericke and Blessing, 2011). Researchers already investigated and compared design process models (Wynn and Clarkson, 2005, 2017; Gericke and Blessing, 2011, 2012; Chakrabarti and Blessing, 2015). Following the methodology based on Gericke and Blessing (2012), Chakrabarti and Blessing (2015), and (Wynn and Clarkson, 2005), a range of design process models were qualitatively compared. Aspects from Wynn and Clarkson (2005) in terms of shape and the integration of other competencies has been added to the analysis. Thus, a range of design processes was investigated in terms of type of support, stage- or activity-based description, orientation, focus of activities, form, as well as the integration of other disciplines (see Figure 16).

		type of support				stage-based activity-based				strategy							Solution- or problem-oriented				Design- or project-focused				approaches				model type				
Author	Year	process model	design methods	process + methods model	management methods	stage-based	activity-based	combined	not clear	stepwise	cyclic	decomposing	iterative	abstracting/concretising	other	not clear	solution-oriented	problem-oriented	not applicable	not clear	design-focused	project-focused	combined	not clear	abstract	procedural	analytical	not clear	descriptive	prescriptive	combined	not clear	Integration of other disciplines
Jones	1963	x				x				x							x				x				x				x				
Lawson	1980	x				x					x						x				x				x				x				
Cross	1994	x				x				x			x				x				x				x				x				
French	1985	x				x				x			x					x			x					x			x				
Archer	1984	x						x					x				x				x					x				x			
Pahl & Beitz	1996	x		x				x		x			x				x				x					x				x			
Heufler	2004	x			x			x		x			x	x			x						x			x				x			x
Hirsch	2014	x				x				x			x				x				x					x				x			x
IDEO	N.A.	x		x				x		x				x				x					x			x				x			
Bürdek	2005	x						x		x			x							x	x					x				x			
BDC	2005	x				x				x							x				x					x				x			
Sanders	2012	x						x					x					x			x				x				x				
Kumar	2013	x		x			x				x		x	x				x			x					x				x			
NN Group	2016	x		x				x		x	x		x							x			x			x					x		

Figure 16. Analysis of design process models

The analysis shows that the majority of the investigated models are visualized as process models with a stepwise and iterative strategy. Additionally, while all but one process models are stage-based, half of the investigated processes are combinations of stage-based and activity-based models. The majority of models is solution-oriented, design focus, and procedural. Furthermore, there is a balance between descriptive and prescriptive model types. Lastly, only the minority of design processes considers other disciplines throughout the product development. Considering the aforementioned identified similarities among the models, processes such as the Heufler design process and Hirsch design process appear to be representative models. Additionally, an investigation was conducted to determine the covered stages throughout the product development by each process starting from establishing a need until the closeout of the product (see Figure 17).

Author	Year	Establishing a need	Analysis of task	Conceptual design	Embodiment design	Detailed design	Implementation	Use	Closeout
Jones	1963		■	■	■	■	■		
Lawson	1980		■	■	■	■			
Cross	1994		■	■	■	■	■		
French	1985	■	■	■	■	■			
Archer	1984		■	■	■	■			
Pahl & Beitz	1996		■	■	■	■			
Heufler	2004		■	■	■	■	■		
Hirsch	2014	■	■	■	■	■	■		
IDEO	N.A.		■	■	■	■	■		
Bürdek	2005	■	■	■	■	■	■		
BDC	2005		■	■	■	■	■		
Sanders	2012	■	■	■	■	■			
Kumar	2013	■	■	■	■	■	■		
NN Group	2016	■	■	■	■	■	■		

Figure 17. Stage coverage of process models

As Figure 17 shows, all considered design processes involved the stages of analysis of the task, conceptual design, embodiment design, and detailed design. Since there is no significant pattern in coverage of stages such as establishing a need and implementation, these stages are be considered for the consensus model.

Based on the previously described investigation, a schematic consensus model of a design process is proposed. It consists of four core stages *Research and Analysis*, *Conception*, *Design*, and *Refinement*. Since a research hypothesis of one conducted design study during the project investigates the impact that extended realities can have on product presentations (see chapter 6.7 MR presentation), a fifth stage is added called *Finalizing*. Figure 18 shows a visualization of the defined consensus model.

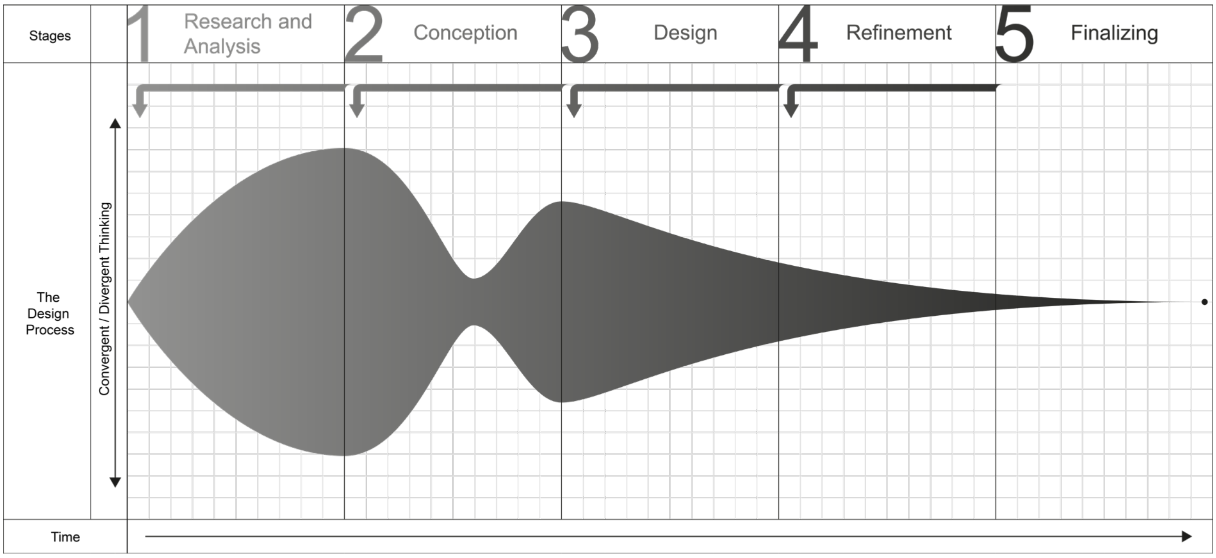


Figure 18. Design process consensus model (source: own representation)

Since a considerable amount of the investigated design process models incorporate visualizations of divergent and convergent thinking (i.e., Double Diamond, Heufler process, Hirsch process), it is also included in the newly defined consensus model. This also applies to the iterative character of the process which is visualized by the arrows above the model.

During the *Research & Analysis* stage, information is gathered. Thus, the designer acquires expert knowledge within the scope of the project (displayed as the divergence in the first stage in Figure 18). This also includes a potential target group analysis and product analysis. Heufler (2004) states that main purpose of the *Research & Analysis* stage is the identification of problem(s). At the end of this stage, a design briefing is drafted which defines all factors affecting the design study. This includes, for instance, target groups, technical and economic demands, environmental impact, and a schedule. For projects that deal with problem statements of future scenarios, it is difficult to collect data on user behaviour. In this case, these factors are assessed with the help of quantitative and/or qualitative interviews or alternative abstract methods. Usually, the definition of the design briefing serves as a basis for moving to the second stage.

In the *Conception* stage, the gathered information is clustered, correlated and questioned. Putting information in relation to one another can lead to new potentials. This forms a synthesis which is displayed as the most converged point during the *Conception* stage in Figure 18. Subsequently, a generative and exploratory search for decisions is conducted (based on Kolko, 2011). The outcomes of this stage are several concepts that are presented to clients and/or the internal management. At this point, the concepts usually range from conservative to futuristic approaches. Finally, the clients or decision makers then select one concept (or sometimes two) that will be elaborated further in the subsequent stages. Once the developed solution approaches are presented externally and/or internally, the designers move to the next stage. A contemporary approach is participatory design (or Co-Design) in which users are integrated in the design process. Beyond user-centred design, human centred design can be improved by this integrative approach (based on van der Bijl-Brouwer and Dorst, 2017). Particularly during this stage, the input of participatory design is advantageous (Steen et al., 2007).

The next stage is the *Design* stage in which variations of the selected concept are created. This stage constitutes the core of the design process (Heufler, 2004). Here, designers combine the logical requirements that were gathered from the previous stages with intuitive and creative approaches. The actual designing of the selected solution approach and its variants happens within this stage, mostly with sketching, CAD models and early modelling for first evaluation tests. Furthermore, alignments with other departments and/or parties take place. Product properties as well as the product language are created. Depending on the project, early and fast prototyping can be connected with great effort. Starting with this stage, the designers follow a convergent process to further define and evaluate the product (displayed as the convergence from stage three to stage five in Figure 18). Once the product properties are defined and integrated into the CAD model, the designers move to the next stage.

The penultimate stage is called *Refinement*, in which the concept is refined with the help of functional models and design models. This also includes the definition of details. Aspects such as production processes, materials, and surface treatments are selected. Extensive user tests are conducted on various aspects including ergonomics, usability, reachability, feasibility, functionality and visibility. Additionally, aspects such as corporate branding are considered within this stage. Once the product is evaluated and a corporate branding is created, the designers move to the last stage.

During the *Finalizing* stage, the results, together with early-stage investigations, concepts, tests and prototypes – are documented. The project's results are presented internally and externally. Since this is a very crucial point in the design process, it is highlighted in Figure 18. After the presentation(s), the focus lies on the implementation of the detailed technical specifications into business processes like production, marketing, and operations.

4.2 Transfer design methods to VR

Based on a literature review as well as internal and personal criteria that were relevant for the chosen case studies, a mind map was created that helped defining and explaining the choice of design methods that were combined with VR in the present dissertation. It includes aspects such as the project stage (since the research objective is to investigate the usage of VR within all stages of the design process), the case studies (that were predefined by the employer), the research objectives (i.e., using VR for problem identification, ideation, evaluation, and presentation of concept), the involved participants including study scale, as well as collected data (see Figure 19). These sets of choices already narrowed down the potential design methods. A final choice of method was made based on personal preferences and relevance for the employer.

Design stage	Case study	Study objective	Participants	Study scale	Collected data
Research and Analysis	Problem identification for guidance systems	Problem identification	Experts	Small scale (<15 pax)	Opinions and preference
Conception	Development of a public transit hub	Concept generation			Behaviours
Design	Immersive CAD prototyping		Lead-users	Middle scale (15-50 pax)	
Refinement	Communication from AV to pedestrian	Concept evaluation			Expertise
Finalizing	Presentation of an information system	Concept presentation	Users	Large scale (50+ pax)	Quantitative data

Figure 19. Mind map for defining design study characteristics

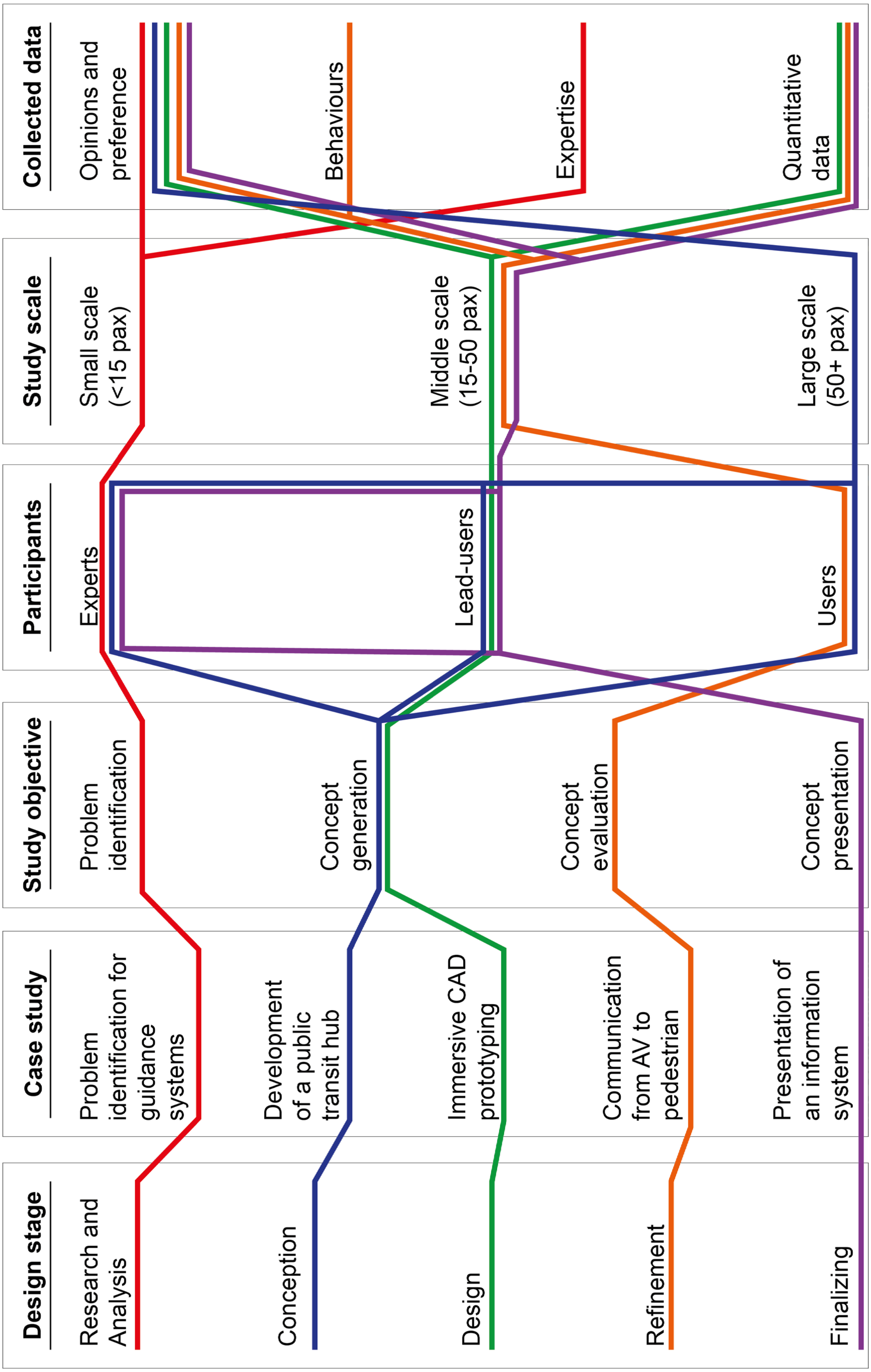


Figure 20. Chosen design studies based on the defined mind map

Following the previously defined consensus process model, one representative design method was derived for each stage of the design process, including the aforementioned study considerations consisting of the underlying research questions, project settings (i.e., budget, capacity, timeframe), as well as intuition of the researchers (see Figure 20). Based on the aforementioned mind map and project characteristics, the following design methods were chosen as representative methods along the design process (Figure 21):

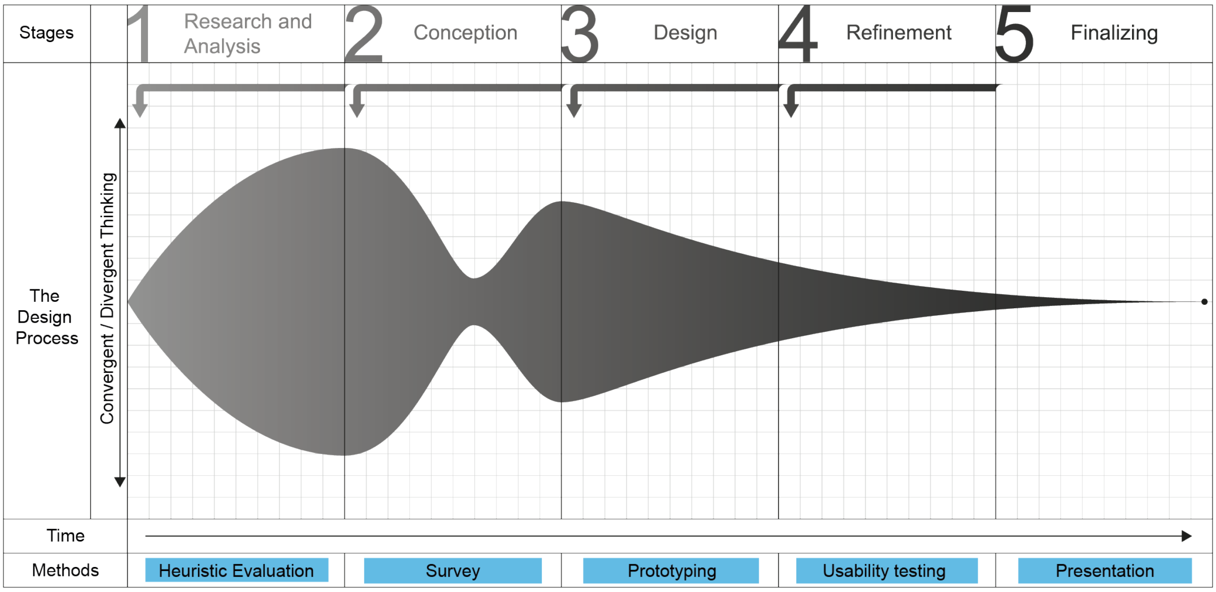


Figure 21. Chosen design methods along the design process

4.3 Preliminary set of evaluation criteria

Similar to the findings of chapter 4.2 Transfer design methods to VR, there is no standardized set of criteria for evaluating design studies and its outcomes. Main reason for this is that usually scopes of design studies are individual and often not comparable to one another. Furthermore, as it was elaborated in chapter 2.1 Design – Tentatively defined, design studies deal with wicked problems and thus, there is not one correct solution but countless solutions. Therefore, design studies cannot be evaluated in terms of correct and incorrect, but in scales such as “more appropriate” and “less appropriate” or “more effective” and “less appropriate” (Cross, 2006; Willem, 1990). Furthermore, outcomes of design studies touch aspects such as practicality and ingenuity, which cannot be evaluated in an objective manner (Willem, 1990).

To simplify the evaluation and comparison of the newly developed VR design methods with conventional design methods however, an attempt was made to derive a preliminary set of general evaluation criteria based on a literature review:

Safety

Researchers should not expose test participants to safety risks, psychological- and social-harm, detract from well-being, or the creation of an ill effect (Webster Jr. and Sell, 2014). This also applies to damage of the used equipment (Mihelj et al., 2013).

In the context of VR for industrial design, the criterion of safety considers the involvement of potential risk and harm for test participants as well as equipment damage while applying the design methods.

Therefore, the following aspects should be considered for the assessment in terms of safety:

- Does the study impose safety hazards and/or risks of harm on test participants?
- Does the study impose risks of damaging the equipment?

Validity

The term validity refers to the extent to which measures correspond to the concepts they are intended for (i.e., how closely do the measured values correspond to the true values of the variable). To be valid, a measure must be appropriate and complete. To be appropriate, the correct measures must be taken (e.g., if the quality of public schools in different cities should be evaluated, the students need to be surveyed and not the teachers). Additionally, a measure is incomplete if just the quality of education is determined by surveying students without considering other factors such as school building, books, labs since these factors are relevant for the quality of education as well. In this case, the measure is incomplete since the measure does not take into account all relevant factors (Rich et al., 2018). Furthermore, validity can be separated into internal and external validity:

- Internal validity: Is the method actually measuring what is intended to be measured?
- External validity: Are the results generalizable? Does the study tell anything about people or situations that were not included in it?

Rich *et al.*, (2018) state that systematic and random errors can make measurements invalid. To reflect this, the aspect of a controlled environment should be included in the consideration of validity.

The term validity can further be differentiated into relative and absolute validity. Relative validity refers to measures of the same order and direction for instance if one measure is taken in a simulator and another measure is taken in a real environment and compared afterward. While for relative validity, exclusively the order and direction of collected measure is sufficient, for absolute validity the numerical values of both systems need to be identical (Blaauw, 1982; Gaito, 1964).

In the context of using VR for industrial design, the criterion of validity refers to the degree, to which the method is appropriate to collect the correct measures for the respective case study (i.e., internal validity). This includes measures such as behaviours, preferences, and evaluation of aspects such as usability. However, it is not intended to measure the external validity of generalizing the results since the VR method is exclusively applied for a specific case study. If applicable, the relative and absolute validity of collected measures will be elaborated.

Therefore, the following aspects should be considered for the assessment in terms of validity:

- Is the method appropriate?
- Are the results complete?
- Are there random variables and influences that might affect the measurement?
- Is internal validity ensured?
- Can relative or absolute validity be assessed?

Time and Cost

Time and cost are insightful regarding the feasibility of a project's outcome (Stecher et al., 1997). Depending on the context, the criterion of time could consider the overall time of a project but also the time consumption for the conduct of an experiment while "cost" considers the costs for the development of the method but also the costs connected to the data collection.

In the context of using VR in design studies, the criterion of time refers to the time for the development and conduct of the method whereas the criterion of costs considers the development costs and costs for the conduct in terms of aspects such as human resources, equipment, renting of venue, and remuneration.

Therefore, the following aspects should be considered for the assessment in terms of time and cost:

- The time and cost to develop the respective method
- The time and cost to execute the respective method

Effort

The effort for conducting an experiment as a test participant could have an influence on the outcome of a project (Stecher et al., 1997).

In the context of using VR for industrial design, the criterion of effort considers the complexity for the involved designers to develop the application as well as the effort for researchers and participants throughout the data collection.

Therefore, the following aspects should be considered for the assessment in terms of effort:

- The effort in terms of ease to develop the method as a researcher in consideration of prior knowledge and required skills
- The effort in terms of conducting the experiment as researcher or test participant in consideration of prior knowledge and required skills

The aforementioned evaluation criteria are solely derived from a literature review and not specifically aspect of studies in which VR was already used. Since it is anticipated that for design studies that involve VR, additional evaluation criteria could be relevant, a further investigation is made to confirm the current set of evaluation criteria and if necessary, enhance it with further criteria and further weight the derived evaluation criteria to conclude on their importance for design studies (see chapter 5.1 Expert interviews for defining evaluation criteria and chapter 6.1 Expert interviews and evaluation criteria).

4.4 Summary of problem statements

In the preceding chapters, a range of problems due to current technological advances that lead to accelerated product development processes and product life cycles for industrial designers were elaborated. Furthermore, the sparse usage of using XR such as VR in industrial design leaves the question open how VR can be implemented in activities of industrial designers during the product development. One fact that underlines this problem is the absence of assurance that VR constitutes a suitable data collection tool that leads to valid measures. Moreover, there is no validated framework available that allows the direct comparison of design studies in order to derive differences caused by different approaches such as the usage of different design methods. These problem statements lead to the following definition of research questions for the present dissertation.

4.5 Research questions

Based on the aforementioned problem statements, the following research questions were defined:

Research question 1 (RQ1):

Which criteria are needed to evaluate and compare Virtual Reality methods and conventional design studies in a specific application domain? Answering this research question is based on the previously derived preliminary set of evaluation criteria with the aim to refine them especially considering the objective of including VR into design studies. One hypothesis in this context is that based on the unique characteristics of VR, specific criteria to the technology are required. Furthermore, it is expected that the criteria set needs to be flexible to be adapted depending on the scope of the design studies.

Research question 2 (RQ2):

To which extent can Virtual Reality trigger behaviours with relative or absolute validity compared to experiences in real-life? This investigation aims to derive if participants show comparable behaviours when being immersed in VR to real-life behaviours in order to test its suitability as a data collection tool. One hypothesis for this research question is that previous experience with gaming could influence the behaviours and reactions for participants when being immersed in VR.

Research question 3 (RQ3):

What influence does Virtual Reality have on design studies and the design process? Answering this question aims to evaluate the conduct and outcome of design studies based on the previously derived set of evaluation criteria by comparing the newly created VR methods with two conventional design methods each. It is anticipated that this comparison allows the derivation of the advantages and drawbacks connected to each respective VR method. One underlying hypothesis in this context is that VR has the capability to enhance the outcome of design studies compared to conventional design methods in a way to create new possibilities for developing and evaluating concepts.

Research question 4 (RQ4):

How does the usage of Virtual Reality impact the role of the designer? Answering this research question aims to offer insights, how the usage of VR impacts the way of working of designers during the development of the method and application as well as the data collection. In this context, it is anticipated that the utilization of VR for design studies impacts the designers' roles from conducting conventional activities such as generating concepts and evaluating concepts to providing suitable methodologies and test beds for participatory activities as well as working activities of high interdisciplinary nature.

5 Methodology

A range of methods has been applied in order to investigate the aforementioned research questions (see Figure 22).

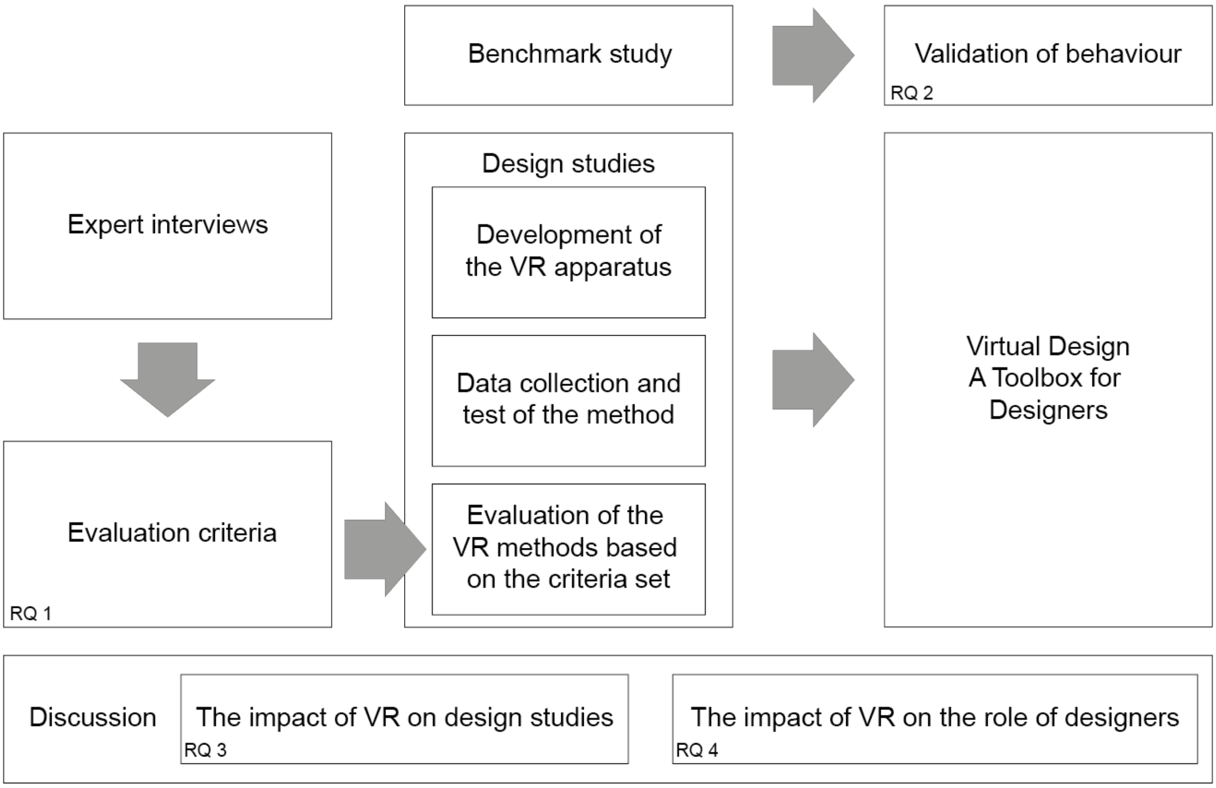


Figure 22. Methodological approach to the dissertation

Based on the preliminary set of evaluation criteria (see chapter 4.3 Preliminary set of evaluation criteria), expert interviews were carried out to define a set of criteria for evaluating design studies (RQ 1). Furthermore, a benchmark study was performed to investigate if VR studies can create behaviours and reactions comparable to real-life experiments (RQ 2). Subsequently, five design studies were conducted including the phases of i) Development of the VR apparatus, ii) Data collection and test of the method, and iii) Evaluation of the VR methods based on the criteria set. Subsequently, the newly developed VR methods were compared to two other conventional design methods in an attempt to derive the impact of VR on design studies (RQ 3) as well as the involved designers (RQ 4) (the comparative design methods are fictional and were not applied). Based on these investigations, a VR toolbox for industrial designers was developed.

5.1 Expert interviews for defining evaluation criteria

In order to verify, weight, and enhance the preliminary criteria set for evaluating design studies that was introduced in chapter 4.3 Preliminary set of evaluation criteria, expert interviews were conducted. Based on the interview methodology of Guion et al. (2006) and Boyce & Neale (2006), the first step was to plan the data collection by clarifying the purpose and objectives of the interviews. Furthermore, the stakeholders were identified. As second step, the interview was defined, involving the clarification of objectives, and developing an interview guide including aspects such as a consent agreement form, an introduction form, a fact sheet with background information, time, and place of interview, the actual interview questions, and a post-interview comment sheet. During the interview, the focus was to make the interviewees comfortable, have a clear and understandable introduction and guide the participants through the relevant topics. While conducting the interviews, the statements were directly transcribed in written form. After the interviews, the transcriptions were sent to each interviewee to ensure the absence of misunderstandings and misinterpretations. Lastly, the statements were categorized to derive schemes of narratives and to identify patterns.

The face-to-face interview took between 60 and 120 minutes per participants and was conducted either at the expert's office or public areas. Overall, seven experts from VR related industries, automotive original equipment manufacturers (OEM), and academia were included in the study. Table 1 shows background information of the involved experts.

Table 1. Background information of experts

No	Company	Country	Background	Affiliation
1	Audi	Germany	Industry	Automotive OEM
2	ETH Zurich	Switzerland	Academia	Cognitive science
3	ImmoPresenter 3D	Germany	Industry	VR Business
4	BMW	Germany	Industry	Automotive OEM
5	flyingshapes	Germany	Industry	VR Business
6	Present4D	Germany	Industry	VR Business
7	Breda University	Netherlands	Academia	VR Research

The structure of the conducted interview was strongly dependent on the respective interviewee. The main purpose of the researcher was to listen and guide the interviewee through the relevant topic. Thus, the structure and interview questions were held flexible for each respective data collection (based on Guion, Diehl and McDonald, 2006). Furthermore, the questions differed between interviewees from academia and industries. Since the participants from academia did not use VR as part of the product development process, the questions were adapted to their respective research field. The following questions were part of the interview for participants in industrial application fields:

- Can you please explain your role at your company?
- How does your company use Virtual Reality during the product development process?
- At which stage of the product development process does this happen and how does the usage of Virtual Reality influence this stage?
- What are the benefits of using Virtual Reality at your company during this stage?
- Are there any secondary benefits that you see during this stage?
- Are there any drawbacks/limitations involved due to the usage of Virtual Reality?
- How was this stage absolved before Virtual Reality was integrated?
- What are prospective strategies at your company regarding the usage of Virtual Reality?
- Is there something, you would like to add or a topic, we did not discuss that you feel is important to mention?

The following questions were part of the interview for participants in academic application fields:

- Can you please explain your role at your institute?
- How does your research involve Virtual Reality?
- Where do you see the benefits and research interest of using Virtual Reality in our research?
- Are there any secondary benefits that you see?
- Are there any drawbacks/limitations involved due to the usage of Virtual Reality?
- How was research conducted in your field before the usage of Virtual Reality?
- What are you plans for future VR research?
- Is there something, you would like to add or a topic, we did not discuss that you feel is important to touch?

The interview transcripts are available in Appendix A. After the interviews, all narratives from the transcripts were clustered into categories such as efficiency-related statements (i.e., regarding the impact on time- and cost- involvement), VR-related statements (i.e., interaction with the virtual environment and immersion), and factors that several researchers mentioned independently from one another (i.e., safety and variability). Based on these statements, a matrix was created that clustered all relevant insights into criteria. Based on the statements and the fact how often the experts mentioned the respective criteria, a weighting was conducted to derive the specific importance of each criterion.

5.2 Benchmark study

Preceding to the conduct of all planned design studies, a benchmark test was conducted in order to investigate to which extent participants' behaviours and reactions in VR are (relatively) congruent to behaviours and reactions in real-life. To allow this, a behavioural observation was conducted. This included a quantitative and qualitative data collection via observations of reactions, time measurements while walking in VR, as well as in-depth interviews after the experiment. Exclusion criteria for participation constituted the presence of any health conditions (i.e., heart condition, epilepsy or similar), any cognitive impairment, or pregnancy. The study was built on three analyses, as described in Table 2:

Table 2. Overview of methods and respective purposes

Method	Purpose	Pax
Observation of behaviours during the VR experiment	Investigating the congruence of behaviours and reactions in VR and real-life	20
Measurement of walking speeds in VR	Comparing the walking speeds in VR with walking speeds in real-life	20
In-depth interviews after the VR experiment	Personal statements regarding participants' behaviour and overall impression of the virtual environment	10

Due to time restrictions, only ten out of the 20 participants were invited to the in-depth interviews after the VR experiment.The test setup consisted of an empty area of 5.0m x 4.2m, in which the participants took part in the experiment. All participants were equipped with an HMD (i.e., HTC Vive). The empty space was tracked with two infrared and laser trackers (i.e., HTC lighthouse). Thus, beyond the capability of tracking the participants' head movements, position changes inside this area could be tracked as well (6DoF). The dimensions of the tracked area were chosen so that the participants were able to walk all required distances physically and without any other form of locomotion (e.g., teleportation). Furthermore, cameras were set up to record movements during the experiment for later analysis. One participant was tested at a time.

A tutorial was initially conducted to familiarize the participants with the virtual environment and the technology of VR. The specific scenario for this was a one-way street section of a city. Each participant had up to five minutes to look and walk around the area with no specific instructions. Once the participants felt comfortable with the technology and surroundings, the briefing for the first task was carried out by the experimenters while the participants were still immersed in the virtual environment.

Within the first phase of the experiment, the participants were placed in a virtual scenario where they were standing on a sidewalk of a one-way street, facing one direction (P) (see Figure 23).

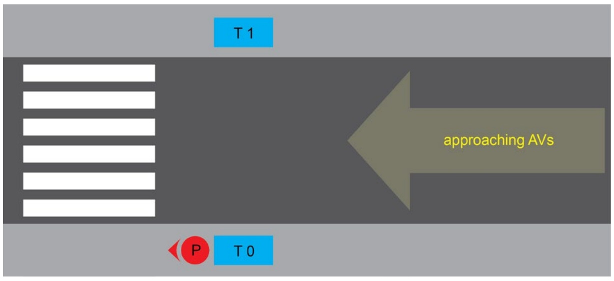


Figure 23. Task Briefing for test phase 1

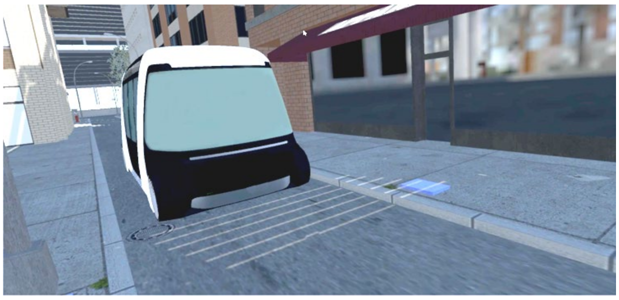


Figure 24. Participant’s first person view during test phase 1

In the beginning of the scenario, a countdown was placed in the visual field of the participants. When the countdown reached the number zero, the participants had to walk to the zebra crossing in front of them. Once the situation was assessed to be safe, the participants had to cross the road via the zebra crossing. At this time, an AV approached (see Figure 24). After the interaction between the participant and the AV, the participant had to reach T1 and turn 180 degrees around. Once the participant reached T1, a new countdown appeared and the new task was to walk back to T0. Consequently, the participants moved back and forth between T0 and T1 via the zebra crossing. Overall, the participants crossed the road ten times in order to test how participants behaved when interacting with AVs in ambiguous situations. During this procedure, the driving behaviour of the approaching AV was altered to establish a range of ambiguous situations.

In the second test phase, the participants stood in the middle of a zebra crossing (T0) (Figure 25) of a one-way street, facing one direction of the street (D1).

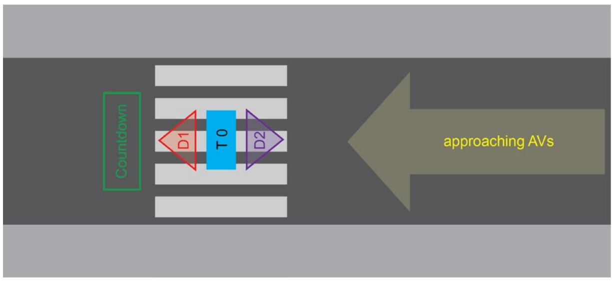


Figure 25. Task Briefing for test phase 2

In the visual field of the participants, a countdown was displayed. When the countdown reached zero, the participants were requested to turn around to face the other side of the road (D2). While doing so, AVs with various driving behaviours approaches the participants (see Figure 26).

Figure 26. Participant's first person view during test phase 2

In one scenario, the AV was approaching and decelerating with moderate speed, while in another scenario, the vehicle executed an emergency brake directly in front of the participants. Additionally, a sound of honking was played. Moreover, in one scenario, the vehicle went through the participants without any deceleration. After facing the vehicle and being exposed to the situation, the participants were asked to turn around 180° again into the starting position (D1). In total, this procedure was conducted 12 times per participant. In order to minimize the risk of distorted results due to the sequence of conduct, a randomized order of approaching vehicles was used.

The goal of the observation was to observe behaviours and reactions while using VR (i.e., movements and sensorial reactions during the two test phases). Thus, all movements were recorded with a video camera and noticeable behaviours were directly noted. In addition, all participants' first-person views were recorded in order to identify which events led to specific behaviours. The goal of the walking speed measurements was to compare walking speeds in VR with real-life walking speeds. Therefore, by using the HMD positioning logs and video recordings, participants' walking speeds were derived and compared to validated data of walking speeds in real-life situations. The goal of the interviews was to collect narratives and rationalizations of people to derive their justification of behaviour in VR, statements about their reactions, as well as general feedback about the VR setting.

5.3 Design studies and transfer methods into VR

A framework consisting of three core steps was defined in order to transfer the chosen design method into VR, involving the development of the VR apparatus, the data collection and test of the method, as well as the evaluation of the newly developed VR design method.

5.3.1 Development of the VR apparatus

Each design study involved a development of the VR apparatus for allowing the application of each respective VR design method in the defined design studies. To increase the replicability of each respective study, the used game engine for the development of the application and the considered hardware for the data collection will be presented. Aspects such as specific environments, simulations (e.g., pedestrian- or traffic- simulations), user interfaces for participants, and locomotion techniques will be shared for all design studies. Besides the VR application, the underlying method that was combined with VR for each study will be explained.

Table 3 shows the available project settings including hardware, internal venues for conducting experiments (external data collection venues are not considered), and available manpower.

Table 3. Available settings for the VR studies

Category	**Item**	**Amount**	**Description**
Hardware	High-performance computer	1	17.3” HP Omen, GTX 1060
	High-performance computer	1	15.6” HP Omen, GTX 1070
	HTC Vive	1	Head-Mounted Display with 6 degrees of freedom including lighthouse trackers and two input devices
	HTC Vive Pro	1	Head-Mounted Display with 6 degrees of freedom including lighthouse 2.0 trackers and two input devices
	Oculus Go	3	Head-Mounted Display with 3 degrees of freedom including an input device
Software	Unity 3D	N.A.	Game engine for developing the virtual environments (from version 2018.1.0 to version 2020.1.1)
Internal venues	Small meeting room	1	Closed meeting room with approximately 15 m²
	Large meeting room	1	Closed meeting room with approximately 60 m²
	Workshop area	1	Open workshop area with approximately 40 m²
Manpower	3D visualizer	1	10 manhours per week
	Student intern (software development and similar)	1-2	40 manhours per week
	Person trained in psychology	1	10 manhours per week

Due to the availability of budget and hardware, CAVE systems were not considered as VR data collection tool but exclusively HMDs. Furthermore, to ensure the conduct of a representative method for each stage of the design process, the timeframe for each project was limited to a maximum of 18 months.

5.3.2 Data collection and test of the method

Besides the data collection for each design study, each respective VR apparatus was tested by applying the newly developed design method in data collection events. Information regarding participants will be shared including, age, ethnical background, and prior experience with VR. Further inclusion and exclusion criteria will be presented for each design study. For each study, the data collection events will be explained and internal and external venues will be described. Besides the meeting rooms that were accessible for experiments (internal venues), this will also cover events such as scientific gatherings, exhibitions, and data collection events (external venues). Furthermore, detailed study procedures will be listed including aspects such as a consent agreement, introduction, actual data collection, and post-processing. One objective of the doctoral project is to have a range of study scales in terms of participants from few experts to large-scale studies. Therefore, information about each respective study scale will be shared.

5.3.3 Evaluation of the VR methods based on the criteria set

Subsequently to collecting data for each design study (see chapter 5.3.2 Data collection and test of the method), the suitability for each newly developed VR method will be assessed based on the set of evaluation criteria defined by the expert interviews (cf. chapter 5.1). Since this is only possible by comparing the newly developed VR method to existing design methods, two representative design methods will be chosen per design study as a basis for comparison. The first method represents more abstract methods that involve comparatively little time and cost and require the imagination of test participants due to the hypothetical nature of the method (e.g., online surveys). The second method represents more tangible methods that are more related to experiments (e.g., on-site observations). This involves additional time and cost, however, in contrast to abstract methods, participants can experience the study set-up without any imagination required. To ensure comparability of the VR method with the two representative conventional methods, the dependent variables for each design study were developed to be congruent for all considered methods (i.e., all methods are aimed to achieve the same result). Within the given time frame of the doctoral project, the focus lies on the conduct of design studies that utilize VR with a great interest on the diversity of the technology in terms of effort, immersion, and interaction. Therefore, the comparative methods without VR are not applied for each study but are based on literature as well as the researcher's experience resulting in a hypothetical comparison.

Since not every criterion was applicable for each study, the considered criteria for each study will be shared independently. In contrast, observations and insights that cannot be categorized into the evaluation criteria are summarized in the category miscellaneous.

5.4 Development of a VR Toolbox

Based on the conduct of all design studies, a toolbox for using VR as an industrial designer was developed consisting of design guidelines and a deck of method cards. The design guidelines contain a range of suggestions that should be considered before and during the development and conduct of VR design methods. The guidelines were derived from observations and lessons learned from the design studies presented in the present dissertation. A card-based toolbox was chosen since the usage of cards in design already has been proven to be advantageous due to its concise information, usability, and potential for customization of the method (IDEO, 2003; Wölfel and Merritt, 2013). Therefore, the aim is to develop a set of method cards for industrial designers as a flexible support that fosters creativity and rigor data collection. While the front page of each method card shows a picture of the actual data collection while applying the respective design method, the back page contains information regarding the application of the method. The structure of the back page is displayed in Figure 27.

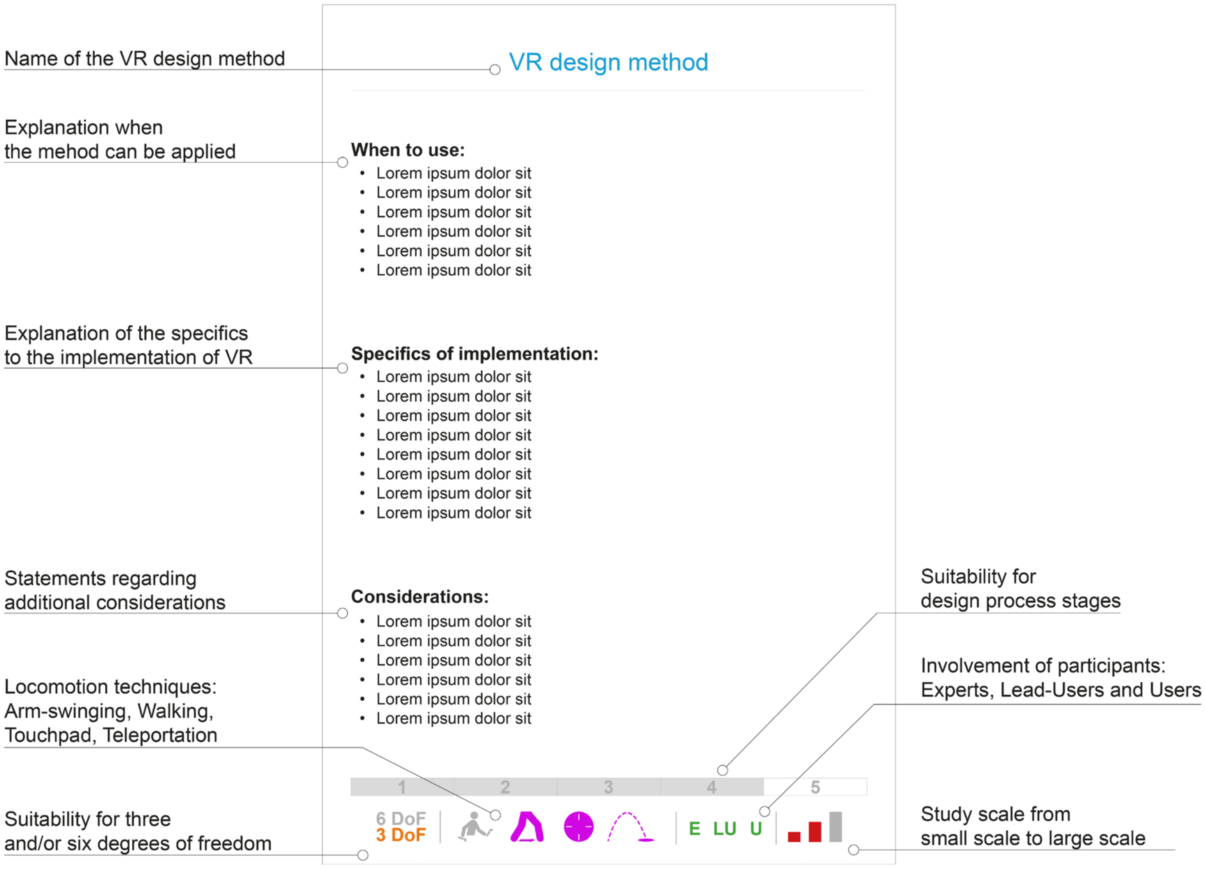


Figure 27. Structure of VR method card

The name of the VR design method that is presented on a specific method card is written on top of the card. In the main body, three categories are used to describe each design method:

1. **When to use:** This paragraph explains in which situations it is advisable to use the presented VR design method.
2. **Specifics of implementation:** This paragraph gives an overview of the specifics to the methods connected to the technology of VR.
3. **Considerations:** In this paragraph, suggestions and considerations are shared when the respective VR design method is applied.

In the bottom part of the method card, a set of icons and abbreviations is listed following different colour schemes. When an icon is greyed, it is not suitable for the described method. When it is highlighted in colour, it is suitable for the described method. The five tiles numbered from one to five above the pictograms at the bottom of the card represent each stage of the design process. When one tile is highlighted in white, the present method is suitable for the respective process stage (e.g., stage one and four in Figure 27). Below, there are additional icons indicating specific characteristics of the present design method. In the left-hand corner, it is indicated whether a three degree-of-freedom (3 DoF) setup and/or a six degree-of-freedom (6 DoF) setup can be used. To the right-hand side of the DoF section, it is indicated which locomotion techniques can be used for the method consisting of arm-swing locomotion, physical walking, touchpad movement, and teleportation. To its right-hand side, it is indicated if the method is suitable for the involvement of experts (E), lead-users (LE), and/or users (U). Lastly, in the bottom right corner, three bars indicate the possible study scale of the respective method. Here, the left bar represents a small-scale study, the second bar a middle-scale study, and the right bar stands for a large-scale study.

6 Results

6.1 Expert interviews and evaluation criteria

Since the backgrounds and application fields of the experts regarding VR differed, the significance of criteria that were described by each expert was different. Thus, the aspect of safety for example only applied to the minority of experts, whereas time and cost applied to all experts. Table 4 shows a weighted summary of expert statements regarding the definition of evaluation criteria. The importance of each mentioned criterion per expert was derived by the amount and emphases of narratives. Beyond the preliminary criteria (see chapter 4.3 Preliminary set of evaluation criteria), the experts mentioned additional criteria such as *interaction*, *immersion*, and *variability*.

Table 4. Expert statements regarding criteria

	Expert 1 (Ind.)	Expert 2 (Acad.)	Expert 3 (Ind.)	Expert 4 (Ind.)	Expert 5 (Ind.)	Expert 6 (Ind.)	Expert 7 (Acad.)
Validity	•••	•	••	•••		•	•••
Time/Cost	••	•	••	••	••	••	•
Variability		•	•	•	•••	•	•
Interaction	•	•	•	•	•	••	•
Safety		•••				•••	•••
Immersion	•	•	•	•		•	•
Effort					•		•

Ind. = Expert with a background in industry; Acad. = Expert a background in academia

For the researchers from the academic field, the aspect of safety for test participants was the most important. One expert from an academic background mentioned: “First of all, the aspect of safety needs to be ensured for everyone. VR allows us to observe people’s behaviours in extreme situations such as fire emergency scenarios while still maintaining a safe environment.” Another expert in the field of VR business for visualising power plants in VR also named safety as one of the key advantages. For experts who apply VR in application fields that do not involve safety issues, the validity of the tool was the most important factor, since otherwise, the usage of VR would not make sense.

The aspect of time and cost was mentioned by every expert. While these aspects were more important for experts from industries, the academic researchers saw this criterion secondary. All experts except one mentioned the advantage of increase variability for VR: For the academic researchers, the usage of VR allows to increase scenarios and/or concepts being tested. One expert in the field of VR for real estate mentioned that VR offers new perspectives for displaying real estate to customers due to the virtuality, such as maps of electronic distribution, or floor plans.

The criterion of interaction was mentioned by all experts as well. There is a consensus that the interaction with the system needs to be suitable for the participants and users and must allow a natural and usable navigation throughout the experience. One expert stated: “The interaction with VR must be as easy as possible for users otherwise there is no acceptance in using it.”

Similarly, the experts mentioned that immersion must be ensured since it is an important requirement for successful experiences to create the feeling for users of being present in the virtual environment. One expert mentioned: “When immersion is ensured, VR is the key for letting users experience scenarios as in real-life conditions.”

Lastly, two experts mentioned that compared to alternative methods, the usage of VR might add additional effort and complexity during the development. Based on the literature analysis and the expert statements, the following hierarchy is derived for the criteria (see Table 5):

Table 5. Weighted evaluation criteria

No	Criterion	Weight
1	Safety	•••*
2	Validity	•••
3	Time/Cost	••
4	Variability	••
5	Interaction	••
6	Immersion	•
7	Effort	•

***only applies for specific case studies**

In summary, the expert interviews led to a set of weighted criteria with the aspects of safety and validity as being most important, followed by time/cost, variability and interaction. Lastly, the aspects of immersion and effort were mentioned. The criterion of safety was chosen as the most important criterion as mentioned by the three experts since the securing of safety for participants exceeds the importance of data collection. However, as it was pointed out, this criterion does only apply to specific case studies in which participants could be exposed to potential harm. On (almost) the same level of importance for data collection, the criterion of validity was chosen since it was pointed out by almost every expert and was verified as the biggest driver for successful data collection. The criteria of time and cost, variability, and interaction were also mentioned by almost every expert. However, its importance was rated less than safety and validity based on the experts' narratives. Lastly, since the relative importance of the criteria of immersion and effort was rated low by the experts, these criteria were also rated as the least important ones.

6.2 Benchmark study

During both test phases of the VR experiment, participants' behaviours were observed. In the first trial of the first test phase, 17 out of 20 people lifted their feet to perform a high step when entering the sidewalk. Several participants even maintained this behaviour until the end of test phase 1 (see Figure 28).

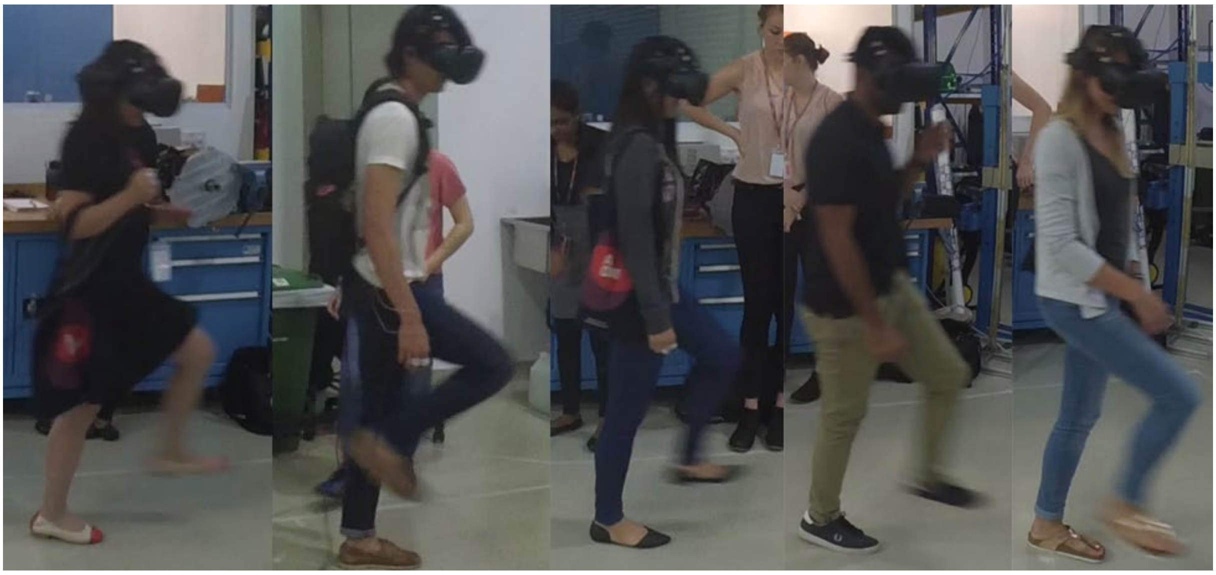


Figure 28. Selection of participants performing a high step when entering the sidewalk

The majority of participants showed walking speeds (~1.5 m/s) and behaviours similar to real life walking speeds and behaviours (e.g., watching the road before crossing and making a high step when stepping on the sidewalk). One participant even walked quicker than in real-life. In contrast, two participants moved notably slower than in real life conditions. One participant did not dare to lift her feet while walking out of the fear of eventual steps she could not see. Even though the experiment was conducted in VR, it was noticeable that more than 50% of the participants carefully looked to the right and the left side of the road, before entering the zebra crossing.

Upon being confronted with approaching AVs in test phase 2, participants showed behaviours such as being surprised, scared, or amused. While some participants raised their hands for protection, others tried to dodge the approaching AV physically by stepping aside or to the back (see Figure 29).

Figure 29. Selection of participants with noticeable reaction in Test Phase 2

The observation of test phase 2 revealed that most participants showed noticeable behaviours when being confronted with approaching AVs.

Within the in-depth interviews, the participants were requested to make statements, narratives, and rationalizations about their experience during the VR experiment. The focus was to collect personal statements of behaviours and attitudes and to identify the aspects that deepened and took away from immersion. Overall, ten participants have been interviewed.

The majority of participants stated that the second test phase was scary, shocking, amusing and very realistic. The participants stated that they were not scared to get injured since they were aware that they were immersed in a virtual environment, although, the participants claimed that the scenario felt very realistic. One participant stated, “after the car hit me, I was just repeating to myself it's not real, it's not real, it's not real. [laughs]”. Another participant claimed, “in VR, the vehicle appears to be coming to you very quickly, but you subconsciously know it's not really going to hit you. It's shocking, but you know you won't die.”. Another participant stated that being run over by the AV in VR felt “really scary” (this was consistent with the behaviour since the person lifted his hands and stepped back). These statements gave insight that the majority of participants found the scenarios very convincing. All participants but two stated that they thought they behaved the same way as they would have in reality. One participant said, “I was aware that it's virtual and whatever I do will not really affect anything. But when I started, at first, I just wanted to jaywalk, but as soon as I stepped on the road and the vehicle appeared, I was taken back and decided not to jaywalk and just take the zebra crossing.”. Eight out of the ten participants claimed that they had the awareness of being immersed in VR during the experiment and that they knew that nothing would happen but claimed that they think they behaved as they would have in real life. Considering all subjective narratives and statements, this gave insight that almost all participants subjectively stated to have behaved in a natural way (i.e., as they would have in reality) during both test phases.

In addition to their assessment of behaviours, the participants were asked for aspects that deepened and took away from immersion in the virtual environment. The participants stated that there were aspects within the VR experience that lowered the immersion. One example was the missing physical step at the sidewalk. Even though it was visible in VR, people could not physically step onto the sidewalk. This fact gave insight why the participants lifted their feet to make a high step when moving onto the sidewalk. Another drawback was the cable management. The participants claimed that they could feel the cable that connected the HMD to the computer on their head, which may have contributed to a diminished immersion in VR. Despite this, the overall impression of participants was that the visuals (i.e., the degree of detail of the AV and the city model), the scaling of the vehicle, the urban furniture, and the sound simulations (i.e., background noises and vehicle sound) positively contributed to the immersion.

In summary, the behavioural observations, measurements of walking speeds, and narratives indicated that participants tend to show authentic behaviours and reactions when being immersed in virtual environments. As the in-depth interviews revealed, aspects such as immersion, cable management, and physical obstacles that are represented in VR are aspects to ensure successful experiments. This led to the general insight that participants behave similarly in VR as in real-life, which was a fundamental requirement for the subsequent design studies and their data collections. A detailed description of the benchmark study can be obtained from Stadler, Cornet and Frenkler (2019b) and Stadler et al., (2020).

6.3 Immersive heuristic evaluation

As it was defined in chapter 4.2 Transfer design methods to VR, the method of heuristic evaluation was chosen to be combined with VR and represent the design process stage *Research & Analysis*. The underlying case study was in the field of guidance systems at transit hubs in an era of autonomous mobility as well as the development of dynamic guidance systems in the same context. The objective of the design study was problem identification. As the conventional method of heuristic already suggests, a small study scale is used involving between five and ten experts in usability and/or field related to the project's case study (Jeffries et al., 1991; Nielsen, 2000; Nielsen and Molich, 1990). Lastly, it was aimed to collect qualitative data and specifically experts' statements, observations, critics, narratives, and suggestions.

6.3.1 Development of the VR apparatus

Table 6 gives an overview of the development of the VR apparatus including aspects such as software, hardware, VR environment, locomotion technique, and time frame.

Table 6. Summary of the VR apparatus (immersive heuristic evaluation)

VR for problem identification	
Item	**Description**
Tested method	Heuristic evaluation
Case study	The development of dynamic guidance systems at transit hubs for autonomous public transport
Software (development)	Unity 3D (2019.1.0)
VR Environment	Public transit hub in Singapore (Boon Lay station) including a crowd simulation consisting of 3D agents. A user interface let participants adapt the environment, specifically the crowd, as well as the serving transportation system (DART). A map lets participants teleport to one of the three entrances. Besides the existing guidance system, nine additional guidance system concepts were implemented. The participants could experience every guidance systems in four scenarios in which specific tasks had to be completed.
Locomotion	• Teleportation (also implemented for Oculus Go) • Touchpad movement (also implemented for Oculus Go) • Physical walking • Arm swing movement
Hardware (software development)	HP Omen 15.6”
Hardware (data collection)	1 X HTC Vive Pro 3 X Oculus Go
Time frame (development of the method and data collection)	12 months
Involved manpower	• 1 Designer: 10 hours per week • 1 Software developer: 20 hours per week

To allow the conduct of the immersive heuristic evaluation, a VR platform was created that let participants experience the existing guidance system of a transit hub in Singapore when an autonomous public transport system (i.e., DART) served the station. The proposed method was based on the heuristic evaluation from Nielsen and Molich (1990) and Nielsen (1992).

Instead of evaluating the UIs with tools such as smartphones, tablets, screens or paper prototypes, immersive VR with the help of HMDs was proposed.

As mentioned before, the chosen case study considered dynamic guidance systems (DGS) at bus interchanges in an era of level 5 autonomous mobility. It was anticipated that due to advantages connected to automation, such as bus platooning and optimized schedules, the localization of buses towards specific berths at a bus interchange may vary throughout the day (similar to an airport where several airlines share the same gate throughout the day). Therefore, passengers at bus interchanges would not be able to rely on prior spatial knowledge to board buses anymore but have to constantly re-localise the required bus berths. Since this could lead to disorientation, additional cognitive effort, and decreased user acceptance improved DGS concepts were tested to evaluate their usability for leading people to the respective destination berth.

The set of general heuristics of Nielsen and Molich (1990) was used as a basis for the evaluation. It consists of nine heuristics including aspects such as providing a simple and natural dialogue, consistency, and feedback. Researchers have already used the general heuristics of Nielsen and Molich (1990) in an adapted way to ensure suitability for the chosen case study (Mankoff et al., 2003; Sutcliffe and Gault, 2004). Since heuristics such as “provide shortcuts” did not apply to the present design study, a workshop was conducted in which the experts had the possibility to adapt the heuristics to be tailored upon the case study’s needs. During this workshop, the experts experienced the virtual environment and were asked to adapt the heuristics accordingly.

The following heuristics were defined for the chosen case study:

- Continuity of information
- Consistency of information
- Visibility of information
- Adequate information
- Comprehensibility of information
- Intuitive and clear interface
- Accessibility for vulnerable users
- Provision of feedback
- Prevention of errors

To ensure a realistic scenario, a transit hub in Singapore (i.e., Boon Lay station) was recreated as virtual environment. The necessary information regarding the transit hub was collected by on-site visits and documentation. Figure 30 shows the virtual environment including the crowd simulation and baseline guidance system.

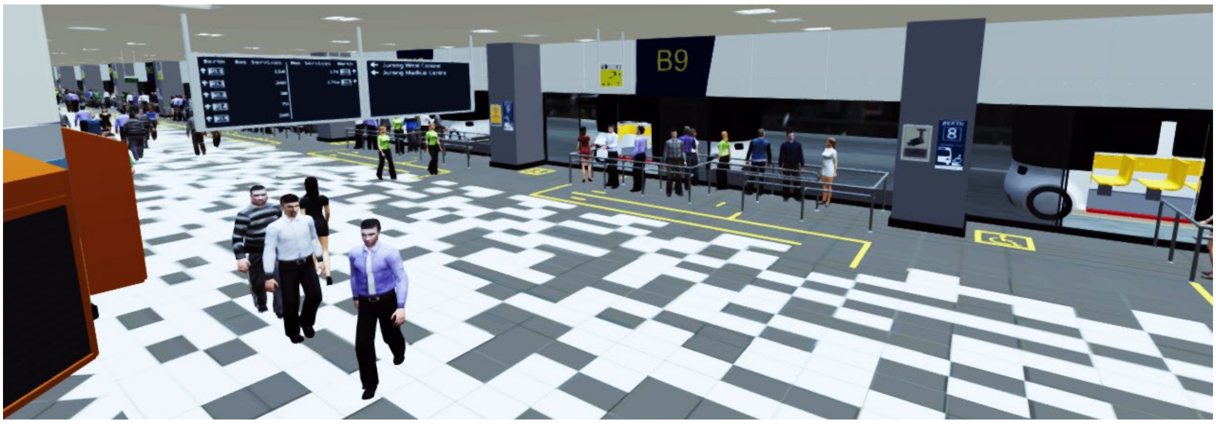


Figure 30. Virtual environment and baseline guidance system

Necessary interaction was implemented to allow the evaluation of the User Interfaces (UI) by the experts. This involved the inclusion of locomotion methods (i.e., touchpad movement, teleportation, arm-swing movement, and physical movement) and possibilities to adapt the environment (e.g., crowd size and arrival time of busses). This functionality was implemented to be accessible to the experts via a VR interface that can be hidden when it is not in use. Figure 31 shows two screens of the VR UIs for modifying the scene (i.e., left: the interface for changing aspects such as crowd level and locomotion technique; right: the interactive map with the option to teleport to the entrances of the bus interchange).

Figure 31. UI of the VR application

A simulation of three-dimensional humanoid agents, representing dynamic crowd levels throughout the day, was integrated that could be manually increased or decreased by the experts (realized via NavMesh). Furthermore, a set of five scenarios involving the completion of specific tasks in the virtual environment was implemented. The scenarios included pre-defined starting points as well as tasks to complete.

The tasks to complete were as follows:

- Start at starting point two and try to enter the bus that drives to Boon Lay Drive
- Start at starting point one and board a bus that drives to Bukit Merah
- Start at destination berth B13 and transfer to the bus that drives to Bukit Merah
- Start at starting point three and find the bus that drives to Jurong East

The arrival times of all busses differed among the scenarios in order to increase the variability for the experts.

A further focus of the application was the integration of a mode that simulates the environment out of the perspective of vulnerable users (i.e., elderly people). This was realized by including a mode that simulates an occlusion of peripheral vision as well as reducing the walking speed of touchpad movement and arm swing movement to 60%. Therefore, the experts were able to experience the virtual environment and UIs from the perspective of a vulnerable user to investigate the system's accessibility.

6.3.2 Data collection and test of the VR method

For the usability test in VR, it was aimed to create a small-scale study. For the conduct, experts from the fields of UI and usability are usually required (Nielsen and Molich, 1990; Jeffries *et al.*, 1991). Since the heuristics for the UIs differed for the present case study, experts from the intended application field of the UIs were involved as well. Since research suggests that a small sample size of five to ten participants is sufficient to identify the majority of usability issues, six experts from the following professions were identified and recruited for the study (based on Nielsen and Molich, 1990; Nielsen, 1992, 2000):

- Design, usability, and UI (Industry)
- Architecture with knowledge in usability and UI (academia)
- Public transport and infrastructure (government)

Since the designers and architects had knowledge in usability and UI, they were paired with experts in public transport to ensure multidisciplinary groups. All experts had moderate experience in using the technology of VR. The experts were grouped into pairs of two with one UI expert present in each group. Consequently, for the conduct of the heuristic evaluation in VR, there were three groups consisting of two experts each, in which one was trained in usability and UI. Table 7 gives an overview of the data collection information for the method of heuristic evaluation.

Table 7. Data collection information (immersive heuristic evaluation)

Time per workshop session (conduct)	~ 200 min
Total amount of participants	6
Data collection venues	Large meeting room (60 m²)

The tests were conducted in a meeting room with 60 m² including a controlled environment with an empty tracked area of 6.2m by 3.8m to allow a six degrees-of-freedom tracking. A HTC Vive Pro HMD was used with HTC Controller and HTC Lighthouse 2.0 trackers. A high-performance notebook was used as hardware for running the simulation (i.e., HP Omen i7-8750H, NVIDIA GeForce GTX 1070, 32 GB DDR4-2666 SDRAM, 512 GB PCIe nvmetm M.2 SSD).

The experts were invited to join a workshop to experience VR and conduct an immersive heuristic evaluation to evaluate dynamic guidance systems at a transit hub in Singapore. After a formal introduction to the case study, the method, the interface, and VR (~0.5h), the experts had time to familiarize themselves with the technology (~0.25h). After clarifying questions, the experts were grouped and started the heuristic evaluation. While one expert experienced the virtual environment, the other expert followed the events on a screen and took notes from the statements of the expert in VR who followed the “think aloud” method (i.e., spontaneously share all observations, findings, usability flaws, and ideas while experiencing the application; based on Lewis (1982)). Even though a think aloud approach is not part of a “conventional” heuristic evaluation but rather a formative evaluation, this aspect has been included to ease the data collection for the experts who are immersed in VR. Figure 32 shows one expert undergoing a scenario and sharing insights while the other expert observes the video footage (showing a first-person view) and notes down statements from the expert in VR.

Figure 32. Experts during the heuristic evaluation

After one expert experienced all scenarios, the experts swapped roles and followed the same procedure. Once both experts experienced all scenarios, the interactive part of the test in VR was finished (~1h). Subsequently, the experts had time to discuss their observations within their group before getting together with the other groups to discuss the experience among all experts (~0.5h). The main objective of the expert discussion was to share usability flaws, ideas, and observations that were identified during the interactive part in VR. The experts prepared a report to document the concluded findings of the heuristic evaluation as precisely as possible. Finally, the experts shared their opinions regarding the usage of VR for heuristic evaluation (~0.25h).

Overall, the data collection was considered successful since a range of observations and shortcomings of the existing guidance system at the transit hub in Singapore were derived. Additionally, the qualitative assessment the experts evaluated VR as a suitable tool for conducting heuristic evaluations in the present application context.

6.3.3 Evaluation of the method

To allow the evaluation of the newly created VR design method, the following comparative design methods were chosen:

Desktop-based heuristic evaluation: A desktop-based heuristic evaluation involves a similar approach and functionality as the immersive heuristic evaluation. However, the application is tested on a computer rather than in VR. By applying this method, experts experience the system via a computer and complete tasks while considering a set of heuristics. While doing so, usability flaws, observations, and considerations are noted.

On-site experiments: Participants undergo on-site experiences of the system. While doing so, the participants are observed by the researchers and errors are noted. After the experience, the participants are asked for observations, narratives, and personal opinions.

Table 8 gives an overview of the advantages and drawbacks of using each of the respective methods.

Table 8. Evaluation of the VR survey and comparative design methods

Criterion	Usability Testing in VR	Desktop-based heuristic evaluation	On-site experiments
Safety	N.A.	N.A.	N.A.
Validity	+	0	0
Time and cost	+	+	-
Variability	+	+	-
Interaction	+	-	+
Immersion	+	-	+
Effort	0	0	-

Safety: The criterion of safety did neither apply to the application of any of the three design methods nor the chosen case study.

Validity: Significant insights were gathered through the immersive heuristic evaluation. Both, severe and minor usability flaws were uncovered by the experts, suggesting that existing guidance systems are insufficient for leading people to destination berths in an era of autonomous public transport.

Besides the uncovering of twelve minor and 10 severe usability flaws for the current guidance system, the experts made a range of statements regarding the validity of the immersive method:

- VR allows for a very realistic and immersive experience.
- VR makes a big difference to the workshops due to its fidelity of spatial awareness and scale.
- The evaluation is conducted under laboratorial conditions.
- VR is a good tool to experience environments and concepts.

Since in VR, the guidance concept could be experienced in several representative conditions (and potentially in any relevant condition), the data set is considered as complete. The experts concluded that VR allowed the evaluation of existing guidance systems in future scenarios in laboratorial conditions and in an immersive way. Therefore, the method was considered as appropriate for the chosen case study which indicates internal validity. Due to the single data collection event, no insights regarding the external validity were drawn. In summary, the experts concluded that the method provided valid results. In a comparative study, it was found out that desktop-based heuristic evaluation resulted in a decreased amount of minor and severe usability flaws which implies a decreased validity of the desktop-based method (see Appendix B). Considering the on-site experiments, participants would always be exposed to changing scenarios since crowd movements cannot be realised an exactly the same manner. Thus, laboratorial conditions could be realised which leads to decreased validity. Furthermore, autonomous transport systems could not be visualized in on-site experiments which could influence participants' behaviours resulting in decreased validity. Due to the consistent direction and order of measurements in comparison with a desktop-based heuristic evaluation, relative validity of the VR heuristic evaluation is anticipated.

Time and cost: The development of the VR method as well as the desktop-based method both required less time compared to other methods such as the on-site experiment since all aspects are realized virtually and not physically. It is anticipated that on-site experiments require a considerable amount of time for planning and organizing the data collection events including agreements with traffic authorities as well as costs for doing so. Thus, the criterion of time and cost is rated lower. During the data collection, no difference between the VR method and desktop-based method was observed. However, it is anticipated that the time consumption of data collection at on-site experiments is increased.

Variability: Both immersive heuristic evaluation and desktop-based heuristic evaluation showed high variability for data collection since the guidance system could be experienced in potentially any desired situation including changeable crowd sizes and scenarios. Changing and/or adapting scenarios and even the guidance system could be easily realised for further tests. Since the guidance systems in on-site experiments would be fixed to predefined locations and running operation of the transit hub could not be adapted throughout the day, the variability adjusting the concepts and scenarios would hardly be possible.

Interaction: The immersive heuristic evaluation as well as the on-site experiment allow natural interaction with the system, including relevant aspects such as peripheral vision, directional noises, and overstimulation. The desktop-based heuristic evaluation is dependent on interaction via mouse and keyboard, which leads to decreased natural interaction with the system.

Immersion: The criterion of immersion is ensured for the immersive heuristic evaluation as well as the on-site experiments since in both methods, participants find themselves directly at the transit hubs with the environment and crowd surrounding them. This fact is not possible in the desktop-based heuristic evaluation which leads to a decreased rating.

Effort: The immersive heuristic evaluation and desktop-based heuristic evaluation are considered similar regarding the criterion of effort. During the development, similar expertise was required. Even though, the interaction with the system is different between the two systems for users, the complexity regarding this aspect is anticipated to be comparable. Regarding the on-site experiment, the effort to realize the scenarios for participants is anticipated to be increased. For instance, this also would involve the presence of actors who would perform in specific scenarios. However, no additional effort for participants is anticipated by using this method during the data collection due to the natural interaction and absence of additional required expertise.

Miscellaneous: A range of miscellaneous observations were made throughout the development and conduct of the design study that are insightful. Firstly, there was no significant difference in the development between the immersive heuristic evaluation and desktop-based heuristic evaluation. For both methods, the expertise of software development was required. Thus, the involved designers relied on the developers' work while overtaking methodological and coordinative work. During the data collection, the role of the involved designers did not change due to the technology of VR. For both heuristic evaluations, the designers facilitated the workshop, introduced the participants to the topic and ensured a

smooth operation during the data collection. During the subsequent interview with the involved participants it became evident that the experts found the VR method as the most promising alternative to collect valid data while having the variability of changing aspects such as crowd and visualize an autonomous transport system. The implementation of the elderly filter for both digital methods was found to be very promising for evaluating systems for vulnerable users such as seniors. The experts also mentioned the usage of the different locomotion techniques including its advantages and drawbacks. While the physical walking and arm-swing movements were advantages to conduct the actual test and complete the scenarios due to its realistic simulation of covering distance, the other locomotion techniques such as teleportation and touchpad movement were advantageous for investigation the existing and newly developed guidance systems in detail. Hence, the experts did not point out one locomotion technique that was the most suitable but stated that the combination of all locomotion techniques allowed a flexible and realistic investigation of all guidance systems.
Main insights of the design study were as follows:

- The data collection involving overall 6 experts was considered successful since usability problems of existing guidance systems in an era of autonomous public transport in Singapore could be identified.
- Compared to desktop-based heuristic evaluation and on-site experiments, heuristic evaluation in VR turned out to be advantageous especially in terms of validity, variability, and immersion.
- During the development of the application, the designers did not take over development work of the application but methodological and coordinative work.
- The role of the designers throughout the data collection was not altered by VR compared to conventional heuristic evaluation.

6.4 Immersive survey

As it was defined in chapter 4.2 Transfer design methods to VR, the method of conducting surveys was chosen to be combined with VR and represents the design process stage *Conception*. The underlying case study was the development of a public transit hub for autonomous busses and specifically the design of its waiting room. The objective of the design study was the generation of concepts. Since the aim was to include a wide range of participants, experts, lead-users, and users were considered for the study. Furthermore, to create a large-scale study, it was aimed to involve more than 400 participants. Lastly, it was aimed to collect qualitative data and specifically participants’ opinions and preferences.

6.4.1 Development of the VR apparatus

The goal of the study was to collect people's preferences regarding the appearance of waiting rooms for public transport (i.e., metro station) especially in multicultural environments such as Singapore. To compare the preferences of people from Singapore with other countries, the test was also conducted in Germany and France.

Table 9. Summary of the VR apparatus (immersive survey) gives an overview of the development of the VR apparatus including aspects such as software, hardware, VR environment, locomotion techniques, and time frame.

Table 9. Summary of the VR apparatus (immersive survey)

VR for concept generation	
Item	**Description**
Tested method	Survey
Case study	Preferences regarding the appearance of public waiting rooms
Software (development)	Unity 3D (2018.3.0)
VR Environment	Interactive room configurator including the variables: • Room dimension • Wall colour scheme (colour wheel) • Brightness • Crowd level (standing crowd simulation)
Locomotion	Teleportation points via ray cast (activated in the user interface)
Hardware (software development)	HP Omen 15.6”
Hardware (data collection)	3 x Oculus Go HMD 64 GB (3 DoF setup)
Time frame (development of the method and data collection)	10 months
Involved manpower	• 1 Designer: 15 hours per week • 2 Software developer: 30 hours per week • 1 3D visualizer: 10 hours per week • 1 person trained in psychology: 10 hours per week

The VR method that was tested in this design study was an immersive survey to collect people's preferences regarding public waiting rooms. Instead of offering open-ended or closed questions to the participants, a virtual configurator was developed that let participants select and visually verify their preferences before the final submission. The application included a consent agreement, a questionnaire regarding background information of each participant, the actual test for data collection, and a questionnaire after the test. The test environment consisted of an interactive configurator consisting of five categories (i.e., room proportion, colour scheme, light, crowd, as well as positioning inside the environment) (see Figure 33):

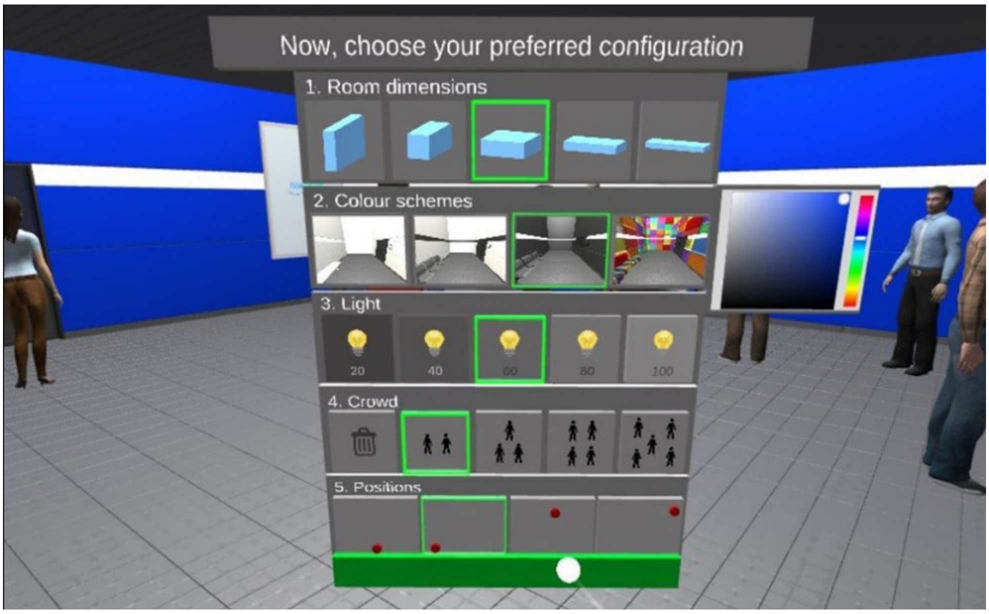


Figure 33. User interface of the interactive configurator

Once the user chose options from the configurator, the surrounding environment automatically updated according to the selection. A crowd simulation including static three-dimensional agents was chosen to represent other waiting people in the waiting room (see Figure 34).

Figure 34. Static three-dimensional crowd simulation

As a locomotion technique, teleportation points were chosen to ensure a usable and simple interaction that suits participants without prior experience with VR. For teleporting and interacting with the interface, the participants used an input device with a ray cast in VR. Users could select options by hovering over a selection option in VR by using the ray cast and pressing the trigger button on the input device. This interaction technique was maintained throughout the whole experiment.

6.4.2 Data collection and test of the VR method

For the immersive survey, it was aimed to create an international large-scale study. Therefore, overall 463 participants from Singapore, Germany, and France were recruited at a range of data collection events. Table 10 shows the data collection information for the method of immersive survey.

Table 10. Data collection information (immersive survey)

Time per participant (conduct)	15 – 45 min
Total amount of participants	463
Data collection venues	• Trade fair, Germany • Exhibition, France • Public science event, Singapore • University information day, Singapore • Two Community centre events, Singapore

Besides collecting data for the chosen case study (i.e., people's preferences for public waiting rooms), the method of conducting an immersive survey was tested. This included the investigation how the usage of VR impacted the data collection for both the involved designers as well as test participants. Furthermore, statements from participants after the tests were collected to assess the suitability of combining VR with a survey considering the chosen case study.

The VR application was tested in Germany, France, and Singapore at a trade fair, an open exhibition, a science event, a university information day, as well as two data collection events in community centres (see Figure 35).

Figure 35. Data collection events (immersive survey)

Therefore, exhibition visitors, passer-by, students, families, children, and senior communities were included in the study to reach out to a diverse group of participants in terms of age, place of living, and prior experience in VR.

Overall, 463 participants were included in the study (50% female, 49% male, 1% prefer not to say) with an overall age range of 8 to 89 years (M=39.88, S.D.=19.96), including:

- 201 passer-by, families, and school classes during a public trade fair in Germany
- 122 visitors of an exhibition about new mobility forms in France
- 57 seniors from two community centres in Singapore
- 22 passer-by during a public science event in Singapore
- 61 students during a university information day in Singapore

The only inclusion criterion for people to participate in the study was to be able to write and speak English, German, or French. At least one researcher was continuously present per HMD during every event to allow an efficient data collection.

Overall, the data collection was considered successful since all people who participated were able to submit background information and a favoured room configuration. Furthermore, based on the submitted configurations, a range of room designs were derived that were considered for further research and development (Figure 36).

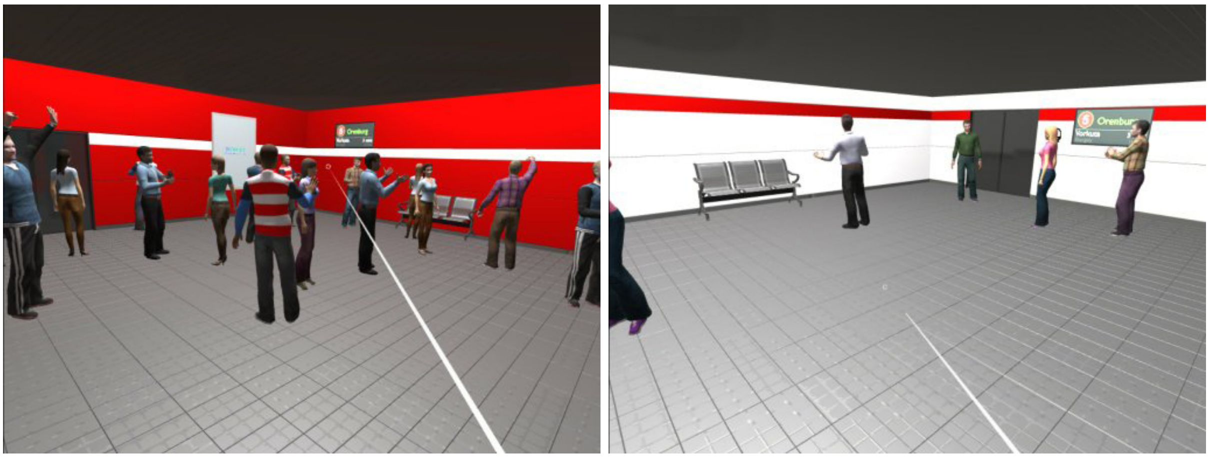


Figure 36. Room configurations preferred by participants

The data collection was also insightful regarding several preferences of people. Specifically, Singaporeans' preferences in wall colours were more likely to be clean and white rather than colourful. In contrast, preferences of French participants were the opposite as they were less likely to choose the white wall texture. When participants chose the wall colours themselves instead of choosing a predefined colour scheme, the most preferred colour was red (independent from place of living). Furthermore, it became evident that individuals between 15-29 years of age were more likely to choose a wall colour scheme with a single colour rather than colourful texture. In contrast, participants between 45-59 years were more likely to choose the colourful scheme. In the age group 60 and above, the participants chose the white texture without any colour. These results showed significant differences in preferences regarding the preferred colour scheme of the public waiting room dependent on the participants' age groups. A further research question was the investigation how the utilization of VR impacted the role of the involved designers throughout the project. Based on the experiences that the involved designers made during the development of the method as well as the data collection, this research question could also be answered. Lastly, a set of design guidelines was defined. A detailed description of the design study and participants' information is given in Stadler, Cornet and Frenkler (2020). The VR experiment was approved by the IRB of Nanyang Technological University of Singapore, No. 2018-12-034.

6.4.3 Evaluation of the method

To allow the evaluation of the newly created VR design method, the following comparative design methods were chosen for the hypothetical comparison:

Digital survey: A computer-based survey that can be displayed on a computer, tablet or Smartphone and uses open-ended as well as closed question types. The development of the survey is conducted via an online tool. It includes the same procedure as the VR experiment, including consent agreement and background information. To collect participants' preferences, pictures of room configurations are shown and each respective participant can select their favoured configuration.

On-site observation: A set of physical mock-ups that each represents a room configuration. Participants are then asked to experience each of the representative room configurations to select their favoured choice. For each room dimension, one 1:1 scale mock-up is built which equals to five mock-ups. Since the amount of possible wall colour schemes cannot be represented by using mock-ups, each representative room is painted in one specific colour scheme (i.e., red, green, blue, yellow, white). Crowd levels are represented by internal actors. After the experience, the participants are asked to name their favoured room and indicate potential adaptations (e.g., change the colour of room two from blue to yellow).

Table 11 gives an overview of the advantages and drawbacks of using each of the respective methods.

Table 11. Evaluation of the immersive survey and comparative design methods

Criterion	Immersive survey	Digital survey	On-site observation
Safety	N.A.	N.A.	N.A.
Validity	+	-	0
Time and cost	0	+	-
Variability	+	+	-
Interaction	+	0	+
Immersion	+	-	+
Effort	0	+	-

Safety: The criterion of safety did neither apply to the application of any of the three design methods nor the chosen case study.

Validity: Significant data was collected showing an effect of participants' age on room proportions and wall colour preferences, as well as an interaction effect of age and place of living on preferences in room brightness and crowd levels. This shows that the VR method enabled the collection of different preferences of individuals from different culture and age group, an indicator for the validity of the VR tool. Furthermore, statements from participants who claimed that the real-time immersive experience allowed them to reflect on their configurations support the validity of the immersive method compared to conventional methods such as picture-based questionnaires. The possibility to visually verify selected room configurations before the submission indicates that the method is appropriate for the intended measurement. Moreover, since all possible room configurations could be experienced in VR, the method allows the consideration of the complete data set. Since the method gave good insights into people's preferences of public waiting rooms, an internal validity for the considered case study is ensured. This fact was also backed up by statements of participants after the data collection. Furthermore, since the data was collected in an international context, specific preferences are generalizable which indicates external validity (the data collection at two community centres showed a correlation of $R = 0.98$). In summary, the method of immersive survey ensures validity of results. Considering the method of an online survey, the criterion of validity is rated lower than the other two considered methods since the stated preferences of participants in online surveys are based on imagination and renderings rather than immersive experiences. Therefore, it is anticipated that the actual preferences are not necessarily congruent with the participants' statements. The method of on-site experiments lets participants verify a set of representative room configurations, however, due to the absence of all room configurations, the data collection is not complete, which results in reduced validity (see chapter 3.2 Evaluation criteria). Due to a lack of direct comparison between the “simulated” design method in VR and a design method involving physical prototyping, relative or absolute validity of measure cannot be assessed.

Time and cost: The development of the VR application involved increased time and cost compared to online surveys due to the necessity of VR hardware (HMDs) and iterative software development. Considering the method of on-site experiments however, the immersive survey was a time- and cost- effective method since the on-site experiments would require the necessity to physically build every room configuration in 1:1 scale. During the data collection, no differences in time and cost are anticipated from the immersive survey to the other methods except the fact that few seniors needed additional guidance throughout the VR experiment which resulted in slightly increased time consumption.

Variability: Both, the VR survey and online survey show high variability for data collection since all possible room configurations that can be derived by the dependent variables can easily be visualized (i.e., as virtual environment for the VR survey and as rendering for the digital survey). Especially for the chosen case study, this is an advantageous aspect since a total amount of 500 room configurations can be created. Due to the fact that for the on-site observation, each room configuration needs to be created in a 1:1 scale, it is infeasible to create all room configurations which leads to reduced variability of this method.

Interaction: Considering the criterion of interaction, both the VR survey and the on-site observation show great advantages since users can experience the room configurations in a natural way which leads to the fact that the interaction with the environment is natural (e.g., peripheral vision and the feeling of crowd). The digital survey however, involves a less natural interaction since all inputs have to be made via mouse and keyboard or finger inputs on a Tablet. Furthermore, interaction such as rotating the head are not possible via online surveys. Thus, natural interaction with the environment for instance by turning the head is not possible.

Immersion: Similar as for the criterion of interaction, immersion is ensured for both methods the VR survey and on-site observation. This is enabled by the environments that surround the participant. In both methods, users are directly placed inside the surrounding room configurations. This means, wherever the participant looks, he/she is still seeing the environment. This fact is not possible in digital surveys since participants can experience the room configurations solely through renderings and/or videos via a display-based electronical device.

Effort: Considering the criterion of effort, all three methods are different from one another. The digital survey involves little effort for developing the application for the researchers, involves little required expertise for doing so, and is simple to conduct for researchers and users. In contrast, the on-site observation requires a huge amount of development effort since at least five 1:1 room configurations need to be built. Additionally, actors need to be present for representing the crowd configurations which leads to increased effort during the conduct. However, there is no additional effort anticipated for the participants during the conduct of the test. Lastly, the immersive survey involved more effort for developers and researchers during the development than for the online survey (including required expertise) but less effort than creating the 1:1 scale prototypes as for the on-site observations. During the conduct, there is additional effort required for the researchers and users since participants without prior experience with VR need an introduction into the technology. Overall, it is anticipated that digital surveys involve the least amount of effort, followed by the immersive survey. The on-site observation is rated to involve the most amount of effort.

Miscellaneous: A range of miscellaneous observations were made throughout the development and conduct of the design study that are insightful in order to answer the research questions. Throughout the whole project, including the development of the application and conduct of the data collection, the role of the involved designers changed to being the project coordinators during the development of the application. This included aspects such as staying on schedule, establishing and maintaining a continuous dialogue among the team members, defining the methodology for rigorous data collection together with the team member with a degree in psychology (including the definition of the questionnaire and variables of the configurator), sharing CAD work with the 3D visualizer (i.e., model the required 3D models), and working together with the software developers to ensure a usable and comprehensible interaction with the VR application (i.e., define the inputs for making selections in VR, define the interfaces, and ensure usability). This interdisciplinary way of working and the collaboration led to the opportunity for all stakeholders, but especially the designers, to acquire expertise from other fields. Furthermore, it was observed that the technology of VR triggered different reactions of participants. While some participants were excited and curious to try the application, others were intimidated and did refuse to try it out (e.g., fear of nausea or addiction to the technology). Lastly, it was observed, that different participant groups showed differences in accessibility to the technology. While especially young participants seemed to be able to intuitively interact with the environment, elderly people needed extensive introductions especially for making inputs in VR.

Main insights of the design study were as follows:

- The data collection of 463 participants is considered successful since out of 500 room configurations, a selection of the three most selected preferences could be drawn.
- Participants stated that VR helped them to visually verify their preferences in VR before the submission which indicates validity.
- Two data collection events in senior community centres showed high correlation of results regarding the collected preferences which indicates reliability of the VR method.
- Compared to the methods of digital survey and on-site observation, the method of immersive survey turned out to be advantageous in terms of validity, variability, immersion, and interaction.
- During the development of the VR platform, the designers acted as coordinators.
- During the data collection, the designers acted as facilitators.

6.5 Immersive prototyping

6.5.1 Development of the VR apparatus

As it was defined in chapter 4.2 Transfer design methods to VR, the method of immersive prototyping was chosen to be combined with VR and represent the design process stage *Design*. The underlying case study was the creation of communication concepts for changing lanes as driver when an autonomous bus is approaching on a dynamic dedicated lane. Thus, the objective of the study was to create an immersive prototyping application (CAD application) that allows users to iterate and create communication concepts inside the manually driven vehicle and/or the traffic infrastructure (e.g., pavement or overhead signage). To evaluate the newly developed application, a further objective was to conduct a comparative test with other commercially available immersive CAD applications as well as desktop-based CAD applications in terms of usability, functionality, time to complete a task, and quality of output.

Table 12 gives an overview of the development of the VR apparatus including aspects such as software, hardware, VR environment, locomotion technique, and time frame.

Table 12. Summary of the VR apparatus (immersive prototyping)

VR for concept design	
Item	**Description**
Tested method	Immersive prototyping (CAD)
Case study	Creating communication concepts for dynamic lane changing in an immersive environment (CAD)
Software (development)	Unity 3D (2019.3.14)
VR Environment	Urban environment (similar to Singapore) including buildings, traffic infrastructure and urban furniture. An autonomous bus and manually driven vehicle can be entered each. Participants have access to a CAD toolbox via the input devices that includes functionality such as the creation, movement, and transformation of primitives, create splines and planes as well as secondary functions such as zooming, changing position and perspective.
Locomotion	Teleportation
Hardware (software development)	HP Omen 15.6”
Hardware (data collection)	HTC Vive Pro
Time frame (development of the method and data collection)	6 months
Involved manpower	• 1 Designer: 10 hours per week • 1 Software developer: 40 hours per week • 1 3D visualizer: 5 hours per week

The method that was tested in this design study was immersive prototyping (CAD). Thus, an application called ImPro (Immersive Prototyping) was created. Since the data collection considering the aforementioned case study (i.e., communication concepts) would have decreased comparability of collected data and would have prevented a within-subject design, the case study was altered and simplified. The task to complete was to create a low-complexity model that was shown to the participants as a picture. Figure 37 shows a summary of chosen methods:

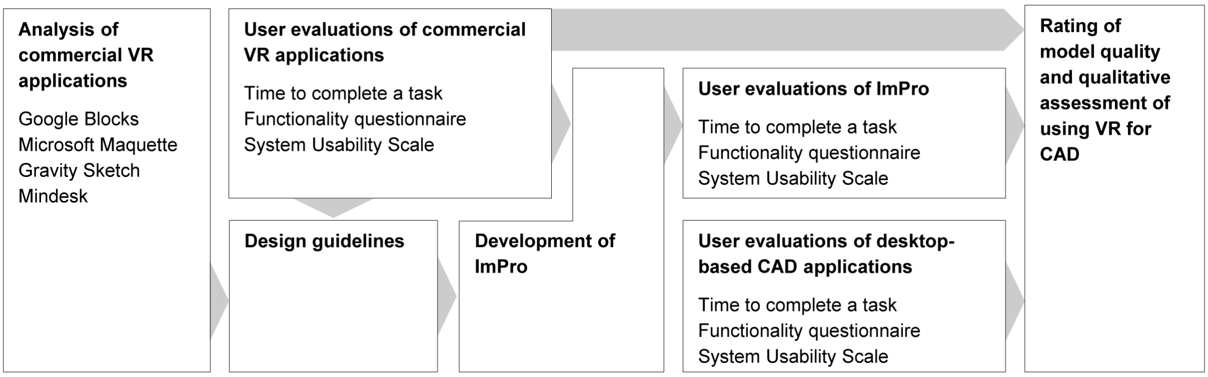


Figure 37. Overview of methods used for developing and evaluating ImPro

In the beginning, an analysis of commercial VR CAD applications was conducted for deriving similarities in functionality for creating and transforming objects as well as scene navigation (see Appendix C). Thus, basic functionality was identified for the implementation into ImPro such as the creation of a box or sphere, rotating objects, and navigation through teleportation inside the scene. The functionality was identified by comparing the available tools (and tool categories) of other commercially available CAD software. Therefore, if a tool (e.g., the creation of a box) was available in all three commercial VR CAD applications, it was identified as "necessary". If a tool was available in two of the three applications, it was labelled as "advantageous". Lastly, if a tool was only present in one of the three commercial applications, it was considered as "not essential". Based on this procedure, the functionality for ImPro was derived.

In parallel to the first user evaluation, the development of ImPro started based on the findings of the analysis of commercial applications. Additionally, the insights from the first user evaluations were incorporated into the development. Figure 38 shows the user interface of ImPro including its functionality.

Figure 38. User interface and functionality of ImPro

By pressing the left thumb-button, the user interface can be opened and closed. The interface is divided into two categories, firstly creative tools for defining volumes and secondly editing tools to transform, move, copy, rotate, mirror, or delete objects. By hovering over the right thumb-button, objects' colours can be adjusted. On top of each input device, the selected tool is displayed (e.g., the hand tool for grabbing and moving objects as displayed in Figure 38). Around the highlighted tool, a circle indicates the colour that is currently selected (i.e., light blue in Figure 38). Above the thumb buttons of both input devices, a red button is available to undo the last actions. To increase the accuracy while the CAD development, two orange spheres are placed a short distance in front of each input device. When the user wants to grab an object, the spheres change colours to green and highlight when the users' input devices intersect with the object that should be moved. To further increase the accuracy while developing, the environment (e.g., urban environment) can be hidden and a grid pattern can be displayed (see Figure 38).

Figure 39. Primitives, brush strokes, and planes placed in an urban environment

Figure 39 shows a selection of placed primitives in an urban environment (left-hand side), an arrow created out of a paint brush (middle), as well as a plane created by pivots (right-hand side).

6.5.2 Data collection and test of the VR method

For the immersive prototyping, it was aimed to create a small-scale study. 14 participants (4 female, 10 male) with an age range of 21 to 31 years (M = 26.3, S.D. = 3.44) were asked to complete a task by using the commercially available CAD applications in VR. All participants worked in academic environment as research assistants and were experts in using desktop-based CAD applications and thus, were considered as lead users. Table 13 shows the data collection information for the method of immersive prototyping.

Table 13. Data collection information (immersive prototyping)

Time per participant (conduct)	45 min – 60 min
Total amount of participants	14
Data collection venues	Small meeting room with a free tracked area of approximately 2.5m x 2.5m

Due to the short timeframe for the design study, the case study of creating communication concepts for dynamic lane changing was altered towards testing the usability, functionality, time to complete a task, and model quality of ImPro compared to other commercially available immersive CAD application as well as desktop-based CAD application.

The procedure of the data collection was as follows. Preceding the test, the participants were introduced to the procedure of the data collection event and a consent agreement was signed. To minimize the risk of distorted results due to the test sequence, the test order for the CAD applications was randomized for each participant (i.e., ImPro, VR CAD applications, and desktop-based CAD applications). Before starting the test for each application, the participants had time to familiarize themselves with the virtual environments and hardware. During the test, the participants had the task to rebuild a low-complexity volume model by using one of the aforementioned CAD applications and its tools. The object solely consisted of primitives that were arranged in a certain way. To ensure comparability, the chosen 3D models had a similar complexity to be created (i.e., using similar tools and requiring the same number of primitives to create the models). One specific volume model was assigned to one commercial application (an overview of 3D models is displayed in Table 14).

The time to complete the task of creating the respective volume model was collected for each participant. The HTC Vive Pro was used with two HTC Vive Pro controllers in combination with a high-performance computer in a 6 DoF setup (i.e., an empty meeting room with an approximately 2.5m² area that was tracked by two diagonally positioned HTC Lighthouse 2 trackers).

Following the user evaluations of the CAD applications, a functionality questionnaire and the SUS were filled out by each participant. Responses for the questionnaires were rated upon a five-point Likert scale (Likert, 1932). The functionality questionnaire consisted of ten questions that were formulated to derive the ease of using the tested application:

Q1: Navigating in the menu was not a problem for me
Q2: Navigating in the scene was not a problem for me
Q3: Changing the scale of the scene was not a problem for me
Q4: Finding the features, I was looking for was not a problem for me
Q5: Creating a 3D primitive was not a problem for me
Q6: Drawing in 3D was not a problem for me
Q7: Deleting an object was not a problem for me
Q8: Modifying an object was not a problem for me
Q9: Duplicating an object was not a problem for me
Q10: Undoing and redoing the last action was not a problem for me

The results from the user evaluation including the functionality questionnaire, the System Usability Scale (SUS), and time to complete the task gave insights into the usability and functionality of each CAD application. While for the VR applications the HTC Vive Pro including its input devices were used, a Microsoft keyboard and mouse were used as input devices for the desktop-based applications.

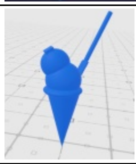
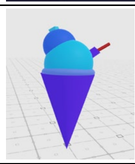
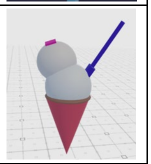
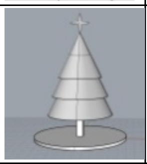
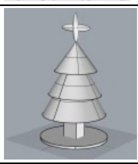
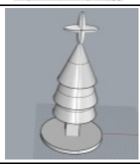
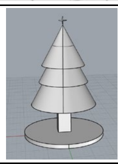
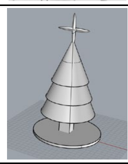
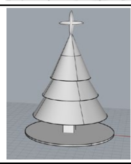
Table 14 shows a summary of the low-complexity models that each participant had to create by using a specific application.

Table 14. Overview of the 3D models that had to be created by the participants

Category	**VR-based**				**Desktop-based**	
Application	Blocks	Maquette	Mindesk	**ImPro**	Rhinoceros	3ds Max
3D Model						

As a last step, the model quality of each application was assessed by three researchers from the same department with a background in industrial design or psychology. The evaluators compared the created volume models with the reference pictures and rated them based on four categories: i) correct number of primitives, ii) correct shapes of primitives, iii) correct placement and orientation of primitives to create the model, and iv), correct proportions of the primitives and 3D model. For each category, up to five points were awarded by the three evaluators. The average score of all summarized categories showed the respective model's quality. After the user evaluations, a qualitative assessment was conducted in which participants were asked open-ended questions about their subjective perception regarding the potential of using VR for prototyping. A selection of models that were created by the participants can be obtained in Table 15.

Table 15. Selection of models created by the participants

App.	**Model 1**	**Model 2**	**Model 3**	**Model 4**	**Model 5**	**Model 6**	**Model 7**
Blocks							
ImPro							
Rhino3D							

Overall, the data collection was considered successful since all participants were able to complete their tasks, statistical analysis could be conducted, and the model quality of each outcome could be rated to derive the advantages and drawbacks of each tested CAD application. Beyond the insight that ImPro offers high usability and lets users create models quickly and with high model quality, a set of design guidelines for creating immersive CAD applications was derived. A detailed description of the design study including the results of the SUS, functionality questionnaire, time to complete the task, and model quality is given in Stadler *et al.*, (2020).

6.5.3 Evaluation of the method

To allow the evaluation of the newly created VR design method, the following comparative design methods were chosen:

Desktop-based CAD: Desktop-based CAD development allows designers to create volume models of products by using a computer as well as a software application. Normally, (3D) mouse and keyboard are used as input devices. By creating and transforming shapes, primitives, and planes, designers are able to transform sketches into volume models that later can be translated into feasible products.

High-fidelity prototyping: While conducting physical prototyping, designers manually create products with various levels of fidelity. This includes low-fidelity prototypes to quickly evaluate ideas often with abstract materials and high-fidelity prototypes that aim to closely resemble the final product including its materials and interaction. Since it is aimed to compare the newly developed VR method to one quick and abstract method and one method close to an experiment, high-fidelity prototyping is chosen for physical prototyping.

Table 16 gives an overview of the advantages and drawbacks of using each of the respective methods.

Table 16. Evaluation of the method of immersive prototyping and comparative methods

Criterion	Immersive prototyping	Desktop-based CAD	High-fidelity prototyping
Safety	N.A.	N.A.	N.A.
Validity	0	0	+
Time and cost	+	+	-
Variability	+	+	-
Interaction	0	0	+
Immersion	+	-	0
Effort	0	0	0

Safety: The criterion of safety did neither apply to the application of any of the three design methods nor the chosen case study.

Validity: Validity for the chosen case study is measured by the quality of created low-complexity model since this factor resembles the designers' intentions while developing prototypes. The higher the quality of model the more valid the result is. Considering the criterion of validity, all three methods show advantages. As the comparative user test showed, participants were able to create models with high quality while using immersive prototyping and desktop-based CAD. This fact indicates validity since the models resemble the users' intentions of shape and scale. The creation of low-complexity models indicates internal validity for the chosen case study however, due to a lack of data collection time during the study, external validity and a complete data set could not be ensured since high complex models could not be considered. Additional data collection would be required to gain insights regarding external validity and the collection of complete data. In the qualitative assessment, participants stated that the immersive prototyping enhanced the sense for scale of the models and that the models could be experienced from any perspective. This is consistent with findings of Keeley (2018) who conducted an experiment for sketching in VR. The results highlighted a greater sense of scale and perspective from participants' side when using VR. These insights indicate better validity of immersive prototyping compared to desktop-based prototyping. In contrast, users mentioned difficulties with accuracy while using VR for prototyping. Thus, both methods were rated similarly. It is anticipated that high-fidelity prototyping leads to the most valid results since participants can actually experience the product including its interaction, materials, weight, and finish while having a perfect sense of scale and haptic feedback. By comparing the VR design method with conventional prototyping methods, a relative validity of measures was substantiated.

Time and cost: In terms of time and cost, both digital methods show great advantages since the development of the 3D models is conducted digitally and not physically. As the comparative user test shows the time to complete the tasks are similar between immersive applications and desktop-based applications except Microsoft Maquette (Microsoft, 2019). Furthermore, the digital model development does not require the designers to procure hardware and materials as long as the computer (and VR equipment) is available. High-fidelity prototyping in contrast is more time-consuming for creating models and involves more costs for hardware, equipment, and tools. Thus, this method is rated lower than the digital methods.

Variability: Similar as for the aforementioned criterion, the digital methods allow higher variability for designers for the development of models since model variations can easily be created by copy pasting. Edge radii or chamfers for instance can dynamically be included, compared, and adapted during the development. Furthermore, actions can be undone and corrected. High-fidelity prototyping in contrast does not offer this variability since every design variant has to be created manually and design corrections are complex to implement. Thus, this method is rated lower compared to the immersive prototyping and desktop-based CAD.

Interaction: High-fidelity prototyping procedures offer the most natural interaction of creating objects for instance by processing wood and applying radii since the designers can constantly check the appearance and surface quality. Furthermore, designers are able to directly check haptic characteristics while creating objects. Nevertheless, it requires knowledge regarding the usage of tools for creating products, including factors such as material characteristics and production techniques. The digital methods are rated lower since the interaction with the object that is created is executed via input devices. Since this kind of interaction is considered less natural than using the designers' hands for creating products, both methods are rated lower than the high-fidelity prototyping.

Immersion: In terms of immersion, the methods of immersive prototyping and high-fidelity prototyping offer the greatest advantage since the objects can be experienced in real scale and in a physical/digital environment that the designers are immersed in. While using the immersive prototyping application, the participants even kneeled and bent their upper body down to investigate and verify details. Another advantage of immersive prototyping is the fact that users can modify the imminent surrounding and thus, can experience the product in any desired application field. Since physical prototypes cannot always be experienced in its actual application field, the method of high-fidelity prototyping is rated lower than the immersive prototyping. Furthermore, desktop-based CAD development does not allow the designers to experience the created object in scale and the visualization is relying on 3D visualizations inside the desktop-based application. Even though the surrounding of the object can be modified in CAD applications, the designers do not have the possibility to immerse themselves into the environment to experience the product that is developed. Hence, the method of desktop-based CAD development is rated lower than the two other methods.

Effort: In terms of effort, all three methods are rated similarly since for applying each method, the designers need expertise. While for the digital methods, the designers need to know the tools and the procedures for creating models, for the high-fidelity prototyping the designers need to be proficient with production techniques, material treatments, software development, and handling complex tools. Since all methods involve their own set of complexity and required expertise, all three methods are rated the same.

Miscellaneous: A range of miscellaneous observations were made throughout the data collection. Firstly, the newly created immersive prototyping application allowed users to create objects as quickly as with the other tested applications, offered high usability, and resulted in the highest model quality compared to the other digital CAD applications. It remains to be identified, what impact the usage of VR could have on the development of high-complex prototypes. The participants stated during the qualitative assessment that the usage of VR during the *Design* phase can accelerate the development time and decision time in general. Furthermore, the participants claimed that the usage of VR was very exciting and made the development of objects very tangible while it fostered creativity.

Main insights of the design study were as follows:

- The data collection of 14 participants is considered successful since it has been proven that the newly created VR application allows designers to create low-complexity models quickly, offers good usability, and results in high model quality.
- Participants subjectively stated that the usage of VR was exciting and fostered creativity.
- The usage of VR allows users to experience objects in 1:1 scale.
- The VR applications lacked in accuracy for creating volume models.
- A set of design guidelines was derived for creating immersive prototyping tools.
- It remains uncertain how VR applications could be used for high-complex models.
- The advantages of the VR method are its time- and cost-efficiency, variability, and immersion.
- The role of the designers throughout the development of the 3D objects did not change while using VR compared to using desktop-based applications and physical prototyping since the designers still were the persons creating the model and using the application.

6.6 Usability testing in VR

As it was defined in chapter 4.2 Transfer design methods to VR, the method of usability testing was chosen and combined with VR and represents the design process stage *Refinement*. The underlying case study was the evaluation of HMIs as communication cues for crossing scenarios at zebra crossings for pedestrians in case of approaching AVs. The HMIs that were tested were display-based animated symbols equipped to the front of the AV as well as projections in front of the AV and at the sidewalks. The objective of the design study was to evaluate the usability of HMIs in terms of effectiveness, efficiency, and satisfaction. As intended participant group, lead-users and users were chosen. Lastly, one objective was to collect quantitative data (i.e., decision times to cross the road and error rates) as well as qualitative data (i.e., task load index, narratives, justifications, and personal preferences).

6.6.1 Development of the VR apparatus

The goal of the design study was to evaluate communication concepts between pedestrians and level 5 autonomous vehicles at zebra crossings. The main channel of communication between manually driven vehicles and pedestrians especially in ambiguous situations, such as at zebra crossings or in car parks, are currently executed mainly via gaze and gestures (Charisi et al., 2017; Llorca et al., 2011; Šucha, 2014). Since in an AV a driver is absent, this kind of communication cannot be carried out in the same manner anymore. The absence of communication increases concerns about sharing the road with AVs as a Human Road User, especially as pedestrian or cyclist. This fact may retrospectively hinder user acceptance and result in safety hazards (Bikeleague, 2014). Therefore, the present design study aims to find out whether explicit HMIs can compensate the lack of communication and thus, encourage acceptance. Overall, two iterations were conducted. Thus, the second iteration already included improvements from the first experiment.

Table 17 gives an overview of the development of the VR apparatus including aspects such as software, hardware, VR environment, locomotion technique, and time frame.

Table 17. Summary of the VR apparatus (usability testing)

VR for concept evaluation	
Item	**Description**
Tested method	Usability testing
Case study	Can explicit HMIs improve the communication between pedestrians and AVs in ambiguous situations?
Software (development)	Unity 3D (2018.3.0)
VR Environment	One-way street in an urban environment and a zebra crossing, including urban furniture and greenery. Two blue tiles on the sidewalk constituted way points to walk to. When approaching the zebra crossing, an AV approached. When approaching, one out of ten HMI concepts was displayed on the vehicle, in front of the vehicle, or on the sidewalk
Locomotion	Physical walking
Hardware (software development)	HP Omen 17.3”
Hardware (data collection)	HTC Vive (6DoF setup)
Time frame (development of the method and data collection)	12 months
Involved manpower	• 1 Designer: 20 hours per week • 2 Software developer: 40 hours per week • 1 3D visualizer: 10 hours per week

The method that is tested in this design study is usability testing. Usability testing is a method in which interfaces are studied under real-world or controlled conditions by observing users completing a set of tasks (Jeffries et al., 1991; Martin and Hanington, 2012; Rubin and Chisnell, 2008). The method provides empirical data from the observation of users while using a product or system.

Basic elements should be included in the research design for usability testing, such as (based on Rubin and Chisnell, 2008):

- Articulation of research questions or test objectives,
- A representative number of users (randomly or not randomly chosen),
- Representation of actual environment,
- Observations of user during the test,
- Interviews of the users after the test,
- Collection of quantitative and qualitative data, and
- Improvement recommendation for the interface.

When applying the method of usability testing, a range of attributes can be investigated which leads to the possibility of quantitative and/or qualitative data collection. The attributes are explained in Table 18 (based on Rubin and Chisnell, 2008).

Table 18. Usability attributes (based on Rubin and Chisnell, 2008)

Attribute	**Definition**
Usefulness	To which extend a product or service supports the user to reach his/her goal with regard to the willingness from the user’s side to use the product or service in the first place
Efficiency	Time, accuracy and degree of completion to reach the user’s goal
Effectiveness	To which extent a product behaves as expected
Learnability	Ability from user’s side to operate a product or system considering a certain level of competence to operate the system after a predefined period of time
Satisfaction	Subjective feelings, perceptions and opinions from user’s side to reveal the user’s satisfaction levels
Accessibility	Access to the products or services that are needed to reach the goal especially for users with disabilities (e.g., temporary or permanent limited mobility)

The task for the users was to cross a road in front of an approaching AV as soon as they assessed the traffic situation to be safe. The task had to be repeated overall ten times with approaching AVs that were equipped with different HMI concepts (various displayed information concepts and technologies for information transmission).

For answering the research questions, the experiments focused on three attributes of usability testing from those defined by Rubin and Chisnell (2008):

- Efficiency: Is the HMI supporting a faster decision-making for crossing the road?
- Effectiveness: To which extent can the HMI prevent wrong behaviour from pedestrians?
- Satisfaction: How does the user perceive the HMI for crossing the road?

The decision times were defined as the duration from when the participants saw the approaching AV until they started to cross the road. Regarding the error rates, participants' behaviours were noted as incorrect when they started to cross the road when the AV executed its right of way. The development and conduct of the experiment followed a list of basic elements that need to be considered in the methodology of usability testing including the definition of research questions, determining a representative amount of users, a realistic virtual environment, and the collection of qualitative and quantitative data including user observations during the tests (Rubin and Chisnell, 2008).

The first iteration of the experiment is based on a method for data collection and evaluation within VR, as described in (Stadler et al., 2017; Stadler, Cornet, Novaes Theoto, et al., 2019). Since the focus of this test was to determine the general support of HMIs, technology to display the HMIs was neglected. Thus, a simple screen-like surface was put in front of the approaching vehicle that displayed the respective concept (see Figure 40).

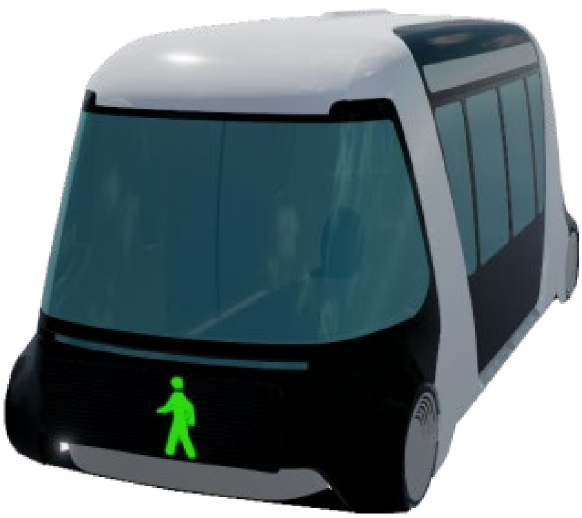


Figure 40. AV with HMI concept (Traffic light)

In each scenario, an AV that was equipped with an HMI concept approached the participant. The HMI concepts indicated whether it was safe for the test person to cross the road or not. To achieve this, each HMI concept consisted of one “Cross” symbol and one “Don’t Cross” variant. The HMI concepts included the commonly comprehensible red and green colour combination, used at Singapore’s traffic lights, in which green is used for indicating that the pedestrian has the right of way (Figure 41).

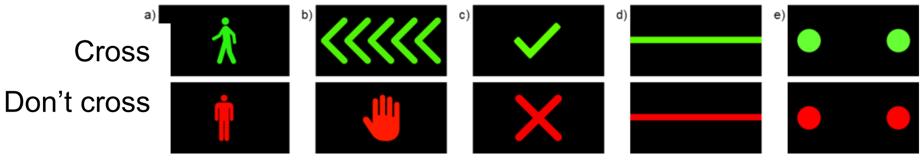


Figure 41. HMI concepts (first iteration)

The virtual environment constituted an inner-city traffic scene that consisted of a one-way street with two adjoining sidewalks, several buildings, public furniture (benches, bus stops, etc.) as well as trees, streetlamps and fire hydrants (see Figure 42).

Figure 42. Virtual environment of experiment 1

Implicit information like gap distance, deceleration speed, engine sound and driving behaviour of approaching vehicles are key indicators for indicating the vehicles’ intentions (Fuest et al., 2018; Pillai, 2017; Song et al., 2018). Since the purpose of the experiment was to find out if specifically explicit HMI concepts can support the communication, implicit cues were neglected for the first iteration. Therefore, the vehicles’ deceleration, active driving behaviour, and engine sounds were neglected.

The general feedback of the first iteration was reviewed and implemented into the second iteration for further improvement of the experiment. This included a refined city environment as well as an adapted test scenario (see below). The main goal of the second iteration was the comparison of selected HMI concepts in consideration of used technology to transmit the information to the pedestrian. The task scenario for the participants in the second iteration was similar to the task procedure of the benchmark test, but with a focus on the evaluation of the HMIs (see chapter 5.2 Benchmark test).

While the control group did not display any information, the remaining nine concepts showed HMI concepts that consisted of various information displayed with different technologies (i.e., laser projection on road/sidewalk/zebra crossing or display-based) (see Figure 43). The zebra crossing was implemented into this scenario to avoid motivating participants to jaywalk as it was the case in the first iteration. Thus, the HMI concepts were not separated in positive or negative information as it was in the first iteration but showed solely positive information that grants the right of way to the participant. Instead, the HMIs indicated the AVs demand to resume driving after five seconds of standing in front of the zebra crossing.

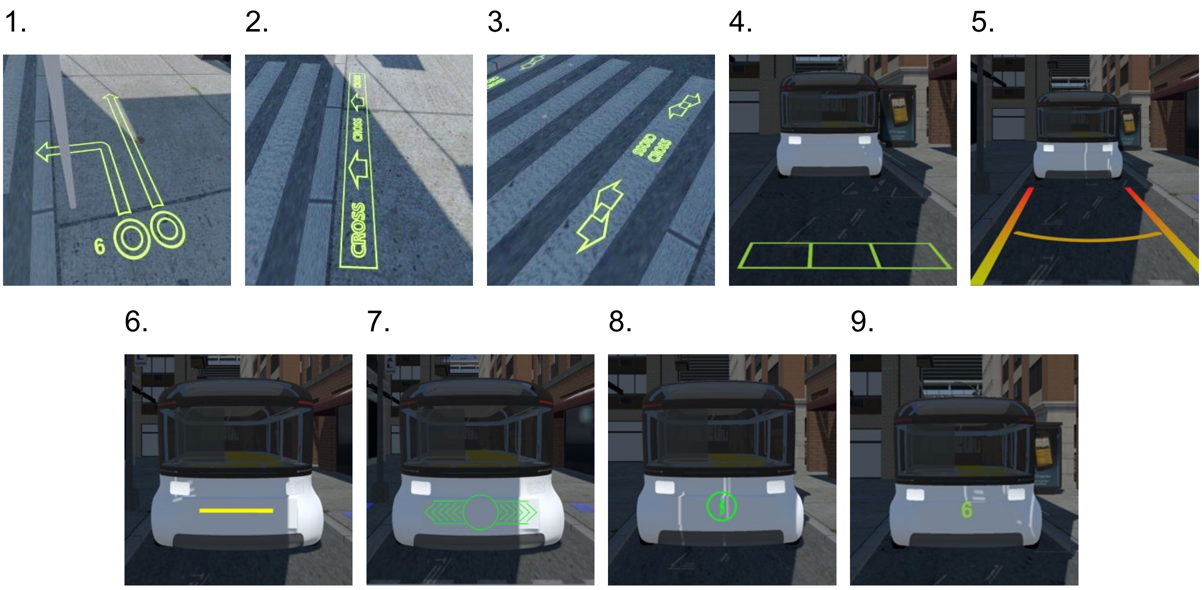


Figure 43. HMI concepts of experiment 2

The virtual environment constituted a refined version of the environment used in the first iteration. Thus, the density of buildings, textures, lighting, urban furniture, and the basic city noises were improved (see Figure 44).

Figure 44. Virtual environment of the second iteration

6.6.2 Data collection and test of the VR method

For the present study (including both iterations), it was aimed to create a mid-sized study. Therefore, overall 37 participants from Singapore were recruited. Table 19 gives an overview of the data collection information for the method of usability testing.

Table 19. Data collection information (usability testing)

Time per participant (conduct)	25 min
Total amount of participants	37 (18 in iteration 1 and 20 in iteration 2 including one data collection error)
Data collection venues	Workshop area with a free tracked area of 5.0m x 5.0m

Besides evaluating HMI concepts for autonomous vehicles, the method of usability testing in VR was tested. This included aspects, such as collecting data such as walking speeds, error rates, satisfaction levels as well as behaviours in VR.

The data collection of both iterations was conducted in an empty area of 5.0m x 5.0m in the internal workshop (see Figure 45).

Figure 45. Workshop area

In the first iteration, a total amount of 18 participants (39% female, 61% male) with an age range of 23 to 36 years old (M = 27.20, S.D. = 3.54) was tested. The ethnic distribution[3] of all participants was as follows: 10 Chinese, 2 Malay, 1 Indian, and 5 participants with other ethnicities. In the second iteration, data from overall 19 participants (37% female, 63% male) were collected with a range of 23 to 34 years old (M = 26.80, S.D. = 2.78). The ethnic distribution of all participants was as follows: 7 Chinese, 2 Malay, 3 Indian, and 7 participants with other ethnicities. For both experiments, no differences in results were measured due to the demographics of participants.

Overall, the data collection is considered successful since it could be answered that HMIs (independent from the specific concept) improve the crossing behaviours of participants (first research question). Furthermore, based on the collected quantitative and qualitative data the tested HMIs could be ranked (second research question). The results indicate that display-based HMI concepts led to less decision time to cross the roads as well as fewer errors. The qualitative data collection confirmed this insight. The ranking of HMIs shows correlations of results of other researchers (Deb, Carruth, et al., 2017; Pillai, 2017). A detailed description of the design study is given in Stadler *et al.*, (2017, 2019) and Stadler, Cornet and Frenkler

[3] Due to Singapore's multiculturalism and four main ethnicities of citizens (Chinese, Malay, Indian, Others), a homogenous ethnic distribution of participants was required to ensure a representative sample size for Singapore's citizens.

(2019b). The experiment was approved by the Institutional Review Board (IRB) of Nanyang Technological University of Singapore, No. 2018-06-048.

6.6.3 Evaluation of the method

To allow the evaluation of the newly created VR design method, the following comparative design methods were chosen for the hypothetical comparison:

Structured questionnaire: The method of structured questionnaires is utilized by a range of researchers in the field of pedestrian safety for AVs to investigate general attitudes towards AVs and how trustful the technology is perceived (e.g., do users trust AVs to make critical decisions) (Deb, Strawderman, et al., 2017; Dey and Terken, 2017; Hulse et al., 2018; Lagström and Lundgren, 2015; Mahadevan, 2018; Matthews et al., 2017; Rothenbücher et al., 2016; Zimmermann, 2008). Using structured questionnaires is a time- and cost-effective way for collecting statements of participants regarding thoughts, feelings, perceptions, behaviours, or attitudes with little effort involved (Martin and Hanington, 2012). Usually, in structured questionnaires participants write down their answers to specific questions. Here, the questions can be open-ended to collect in-depth responses, whereas close-ended questionnaires are easier to numerically analyse (Martin and Hanington, 2012). Five- or seven-point Likert (1932) scales are regularly used in this regard. In the present study, the questionnaire is treated as containing open-ended questions.

Wizard-of-Oz: As mentioned in chapter 3.5 VR for concept evaluation, the method of Wizard-of-Oz lets participants experience a system that appears to be fully working and real while the researchers perform behind the scenes to create this simulation, even though the system is not fully working or functioning yet. This method has already been utilized by several researchers in the context of pedestrian safety to investigate actual behaviour from participants when being confronted with a transport system that appears to be automated (Clamann et al., 2015; Dey and Terken, 2017; Lagström and Lundgren, 2015; Mahadevan, 2018; Matthews et al., 2017; Rothenbücher et al., 2016). In the field of AVs, this can for example be achieved by hiding a car driver in the driving seat (Rothenbücher et al., 2016).

Table 20 gives an overview of the advantages and drawbacks of using each of the respective methods.

Table 20. Evaluation of the method of usability testing and comparative design methods

Criterion	Usability Testing in VR	Questionnaire	Wizard-of-Oz
Safety	+	+	-
Validity	+	-	+
Time and cost	0	+	0
Variability	+	+	0
Interaction	+	-	+
Immersion	+	-	+
Effort	0	+	0

Safety: In terms of safety, both methods usability testing in VR and questionnaire ensure highest standards since during the data collection, participants are not actually approached by vehicles. Therefore, at any time of the data collection safety is ensured for participants and equipment. In Wizard-of-Oz experiments however, participants are approached by actual vehicles with altered driving behaviours and various speeds (cf. 3.5 VR for concept evaluation) which could lead to inappropriate behaviours of participants resulting in potential safety hazards. Therefore, it is anticipated that even in a controlled environment the safety risk for participants and equipment is increased when conducting Wizard-of-Oz studies. In this context, Deb, Carruth, *et al.* (2017) concluded: “The use of a simulator for pedestrian research has many benefits over real-world studies. The most important benefit is safety – a virtual environment displayed in a lab clear of obstacles provides a minimal level of risk to the participant.”

Validity: Since in structured questionnaires participants have to state their believed behaviours in a written form instead of actually behaving in front of a vehicle, validity of results cannot be ensured (similar to chapter 6.4.3 Evaluation of the method). Considering VR usability testing as well as Wizard-of-Oz studies, researchers conclude that both methods are appropriate to collect data and ensure validity since the simulations allow participants to actually feeling approached by AVs (Deb, Carruth, et al., 2017; Rothenbücher et al., 2016; Stadler, Cornet and Frenkler, 2019a; Zimmermann and Wettach, 2017). Since a range of researchers used both methods in the present application field and state internal validity of the methods, it can be anticipated that both methods are also generalizable and therefore imply external validity. By comparing the walking speeds of participants in VR as well as average walking speeds in real-life conditions, absolute validity can be anticipated after a time of familiarization in VR (cf. chapter 6.2 Benchmark study).

Time and cost: In terms of time and cost involvement during the development and conduct of the study, it is anticipated that the method of structured questionnaires has benefits over the other methods since no expensive hardware or development of applications and visualizations is required. This also reflects statements of Martin and Hanington (2012) who claim that questionnaire is a cost- and time-effective method. Comparing the VR usability testing and Wizard-of-Oz study shows various advantages and disadvantages. Pillai (2017) states that compared to Wizard-of-Oz approaches, using VR is cheaper. Deb et al. (2017) also state that the VR equipment is within a price range so that almost any lab could afford such an equipment and work with VR. Both of the statements indicate advantages of VR usability testing over Wizard-of-Oz studies. However, the development time of VR simulations may not be underestimated. While for Wizard-of-Oz studies, exclusively the HMI concepts need to be visualized and a screen needs to be assembled to a vehicle, in VR studies, a whole environment needs to be developed and interactions need to be defined. Furthermore, it is anticipated that acquiring hardware for the VR experiment (i.e., HMD with 6DoF and high-performance computer) is similar to acquiring hardware for the Wizard-of-Oz study (i.e., screen, mounting equipment, renting a car, renting a venue). Therefore, both methods are overall rated similarly in terms of time- and cost-involvement.

Variability: The methods of structured questionnaire and VR usability testing are rated high in terms of variability since a range of concepts and scenarios can be visualized with ease. Even though, this also applies to Wizard-of-Oz studies, the implementation of different communication technologies such as laser projectors requires additional steps such as acquisition, programming, and assembly. Furthermore, there is only a certain amount of technologies mountable at one vehicle. Thus, the variability of Wizard-of-Oz studies is rated lower compared to the other two methods.

Interaction: In terms of interaction, VR usability testing and Wizard-of-Oz study show a very natural interaction during the experiments since participants can naturally interact with the system by walking and looking around, similar to a real-life condition. The structured questionnaire only allows a less natural interaction since all inputs have to be made via mouse and keyboard. Thus, natural interaction with the environment such as looking around is not possible.

Immersion: Similar to the criterion of interaction, VR usability testing and Wizard-of-Oz study both ensure immersion into the environment and scenarios. In both methods, participants find themselves in an environment with a street to cross. This is even ensured when looking around. Participants who conducted the VR usability testing even lifted their feed when entering the sidewalk which indicated great immersion (see chapter 6.2 Benchmark test). Since in structured questionnaires, participants are not immersed in the environment of data collection at all, it is rated lower compared to the other methods.

Effort: In terms of effort, the method of structured questionnaire involves the most advantages since the development and conduct of this method does not require specific expertise or excessive number of man-hours. The method of VR usability testing and Wizard-of-Oz both require more effort, especially during the development. A considerable amount of expertise and man-hours is required to develop the VR environment for the VR study, whereas the Wizard-of-Oz study requires effort and man-hours for the development and mounting of hardware on the vehicle as well as people present during the data collection. Therefore, both methods are rated lower than the structured questionnaire.

Miscellaneous: A range of miscellaneous observations were made throughout both iterations of the design study. Firstly, it became evident that the involved designers were dependent on the software development and therefore, focused more on the methodology of the study. Instead, a strong and continuous dialogue was established between the involved designers and software developers. And secondly, during the data collection, the involved designers bridged the gap between users and VR through a thorough introduction and guidance through the experience. It was observable that participants who were hesitant in the beginning loosened up after the tutorial for instance by increasing the walking speed. One participant did not lift her feed while walking in the beginning due to the fear of hitting obstacles. After finishing the tutorial, however, her walking speed and behaviour was comparable to real-life conditions.

Main insights of the design study were as follows:

- The data collection of 37 participants in two iterations is considered successful since it has been proven that HMIs support participants while crossing the road at a zebra crossing when AVs are approaching.
  - When the approaching AVs were equipped with HMIs, decision times of participants decreased when crossing the road.
  - When the approaching AVs were equipped with HMIs, error rates of participants decreased when crossing the road.
  - Participants subjectively stated that HMIs supported crossing the road.
  - Display-based HMIs showed better results than projection-based HMIs.
- The data collection was conducted with ensured safety for participants at all times.
- The advantages of the VR methods were safety for participants, validity of results, variability of testing HMIs, natural interaction with the system as well as immersion.
- During the development of the VR platform, the involved designers were responsible for the methodology, HMI concepts, as well as 3D visualizations however, a dependency on software development was observable.
- During the conduct, the involved designers hosted the data collection events, including introduction to the topic, (dis-)assembly of the equipment, as well as qualitative data collection (i.e., questionnaires and interviews).

6.7 MR presentation

As it was defined in chapter 4.2 Transfer design methods to VR, the method of MR presentation was chosen to represent the design process stage of *Presentation*. The underlying case study was the presentation of a public transport information system at bus stops for level 5 autonomous public busses in Singapore. The objective of the design study was the presentation of a product/system by using an MR application and to measure the impact that the technology has on usability and acceptability compared to conventional presentation techniques.

6.7.1 Development of the MR apparatus

The goal of the study was to conduct product presentations with MR technology and measure the impact, the technology has on (perceived) usability of the system (collected by using the SUS), as well as technology acceptance (collected by using the Technology Acceptance Model (TAM)). Table 21 gives an overview of the development of the VR apparatus including aspects such as software, hardware, VR environment, locomotion technique, and time frame.

Table 21. Summary of the VR apparatus (MR presentation)

MR for product presentations	
Item	**Description**
Tested method	Product presentation
Case study	Information system for bus stops of an autonomous public bus system
Software (development)	Unity 3D (2020.1) incl. Vuforia
VR Environment	A bus stop in an urban environment including: • A newly developed information system • Simulated busses that approach • Humanoid 3D-agents • Event trigger by using visual triggers
Locomotion	Physical walking
Hardware (software development)	HP Omen 15.6”
Hardware (data collection)	Tablets (i.e., iPad, Samsung Galaxy Tab)
Time frame (development of the method and data collection)	6 months
Involved manpower	• 1 Designer: 10 hours per week • 1 Human Factor Engineer (software developer): 30 hours per week • 1 3D visualizer: 5 hours per week • 1 person trained in psychology: 5 hours per week

The MR presentation was developed by using Unity 3D (Unity, 2020) and the Software Development Kit (SDK) Vuforia (PTC, 2020). Each participant obtained a tablet before the presentation that constituted the MR output device. Figure 46 shows the setup of the MR presentation out of the perspective of a participant.

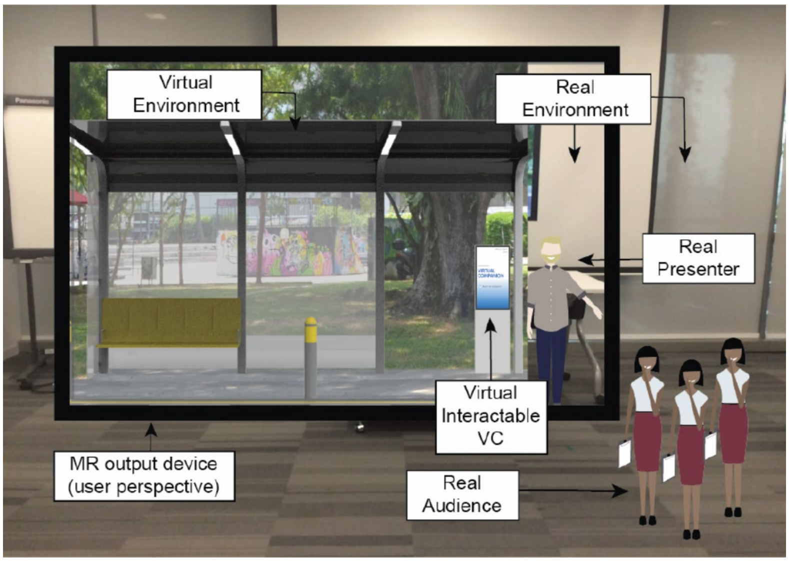


Figure 46. Setup of the MR presentation

The audience saw a virtual bus stop (virtual environment) in the setting of the conference room (real environment). The presenter was visible in the real environment as well as the virtual environment. Next to the presenter in the virtual environment, the interactive information system was visible (see Figure 47. Conduct of the interactive MR presentation). The audience per session consisted of up to four participants.

Figure 47. Conduct of the interactive MR presentation[4]

[4] Disclaimer: The usage of this picture was granted by the depicted person

To allow an interactive presentation and to ensure that all participants progressed through the interactive presentation with same speed, the presenter had an input device in the form of a cube that had visual markers printed on each side. Figure 48 shows the cube with visual markers.

Figure 48. Cube with visual markers

Every visual marker triggered a specific event during the presentation. Since rich contrasts and details are required for flawless image recognition, pictures characterized by a nature background were chosen. Furthermore, a screen next to the presenter was used to show slide-based information (such as the introduction). The users were able to interact with the system by giving inputs into the tablet (e.g., tap at the information system to activate it). Colour coding highlighted interactive content to support users while interacting with the system. Physical walking was chosen as locomotion technique since it provides the most natural and effortless mode of moving. This mode helped the participants to explore the setup and the bus stop on their own and it visually represented scales and distances which caused the feeling of presence.

The virtual environment consisted of the bus stop at a sidewalk, an adjacent road with an autonomous bus that arrives during the presentation, dynamic non-player characters (NPCs), the information system (virtual companion), a surrounding urban environment consisting of buildings, and urban greenery (Figure 49).

Figure 49. Virtual environment

6.7.2 Data collection and test of the VR method

For the present study, it was aimed to create a middle-scale study. Therefore, overall 28 participants were recruited. Table 22 gives an overview of the data collection information for the method of MR presentation.

Table 22. Data collection information (MR presentation)

Time per presentation (conduct)	25 min
Total amount of participants	28
Data collection venues	Large meeting room (60 m²)

The data collection was conducted in a large meeting room of approximately 60 m². Overall, 28 persons (32% female, 68% male) with an age range of 25 to 33 (*M* = 27, *SD* = 2.9) participated in the study. The data collection was set up into two groups, a control group that experienced a conventional presentation and one group that experienced the MR presentation. Each presentation mode involved 14 participants. For the MR group, the mean age was 28 years (*SD* = 2.7) and for the slide-based (PP) presentation 26 years (*SD* = 2.9). The prior knowledge about the slide-based presentation mode and MR presentation mode highly differed throughout the sample size. While 93% of the participants regularly use PowerPoint, 43% of participants never used MR beforehand. The MR presentation and slide-based presentation both took approximately 25 minutes.

Both presentations were structured by the following procedure:

1. Arrival at the test side
2. Signing a consent agreement
3. Introduction to the test and providing background information
4. Exploring the bus stop by walking around in the conference room
5. Scenarios (randomized)
6. Commuter Scenario
7. Tourist scenario
8. Summary of the information system, conclusion, and outlook
9. Subsequent surveys for data collection (see Evaluation)

While for the PP presentation all steps were conducted with the support of PowerPoint slides, the MR presentation included interactive aspects in step four and step five. The remaining steps were supported by the same PowerPoint slides as for the control group.

A total of nine presentations were held to collect the required data (four MR presentations and five slide-based presentations). To increase the comparability of collected data among the groups, the same presenter was involved in all presentations. After the presentations, each participant had to fill out questionnaires such as the TAM questionnaire and SUS. Furthermore, a background questionnaire was requested to be filled out including questions regarding each participant's demographic background (age, gender, and occupation) as well as previous experience of presentation formats (i.e., PowerPoint). The MR group was additionally asked for previous experience with XR including MR.

Subsequent to the questionnaires, qualitative data was collected from the participants by conducting informal interviews. The interviews provided the opportunity for participants to share feedback regarding the MR presentation tool and the information system. Additionally, further thoughts and ideas were shared with the researchers. The answers were qualitatively analysed to improve the MR presentation tool. All answers were categorized into positive feedback, negative feedback pointing out challenges, and suggestions for improving the presentation mode as well as the information system.

Overall, the data collection is considered successful. Even though strong trends were observable regarding the influence on perceived usability of the presented information system, no significant differences were observed between the MR presentation and slide-based presentation. Still, the MR presentation led to higher SUS scores in regard to the information system which indicates a trend. The small sample size however could be an indicator for the derived insignificance. Nevertheless, both SUS scores were above a value of 68, indicating usability above average. Furthermore, the TAM questionnaire resulted in significant differences between the MR presentation and slide-based presentation. The insights suggest that the MR presentation leads to increased technology acceptance compared to slide-based presentations. The MR experiment is based on work by Trauth (2020) was approved by the IRB of Nanyang Technological University of Singapore, No. 2019-12-029.

6.7.3 Evaluation of the method

To allow the evaluation of the newly created VR design method, the following comparative design methods were chosen:

Slide-based presentation: In slide-based product presentations, presenters follow a script that is supported by slides that are usually displayed via a screen or projector. Software applications such as PowerPoint (Microsoft, 2020) and Prezi (2020) allow presenters to visualize content by using pictures, graphs, text, and videos. Usually, slide-based presentations are scripted and one-directional.

On-site presentation: At on-site presentations, the audience experiences a presentation to which the imminent surrounding is relevant. Thus, presenter and audience are located in the application field. The immersive environment supports the presenter to convey their message.

Table 23 gives an overview of the advantages and drawbacks of using each of the respective methods.

Table 23. Evaluation of the MR presentation and comparative design methods

Criterion	MR presentation	Slide-based presentation	On-site presentation
Safety	N.A.	N.A.	N.A.
Validity	+	0	+
Time and cost	0	+	-
Variability	+	+	-
Interaction	0	-	+
Immersion	+	-	+
Effort	0	+	0

Safety: The criterion of safety did neither apply to the application of any of the three design methods nor the chosen case study.

Validity: The immersive presentation as well as the on-site presentation allows the audience to directly experience the presented information system before an evaluation regarding its usability and technology acceptance is given. Thus, internal validity for both methods is ensured. Since the data collection of the immersive presentation method consisted of overall six presentations with highly correlated results, generalizability and external validity is anticipated. Furthermore, in both methods, the audience can experience the whole information system in the actual application field (including noises and distractions) which could impact the perceived usability. Thus, in contrast to the slide-based presentation method, the immersive presentation and on-site presentation both have the potential of a complete data collection. Since in slide-based presentations, the audience does not have the possibility to experience the product directly (i.e., the information system), it is anticipated that the evaluation of perceived usability and technology acceptance is less accurate than the evaluation by using the immersive presentation and on-side presentation. By comparing the collected measures (i.e., usability and user experience), relative validity between the VR presentation technique and the slide-based presentation techniques can be anticipated.

Time and cost: Considering the involvement of time and cost, the slide-based presentation offers the most advantages since the creation of slides is a fast and inexpensive method to support narratives. The development of applications in MR to create immersive presentations involves increased amount of time and costs since a development team, presenter, and other stakeholder constantly have to clarify for instance the story, environment, and interactivity of the application. It is anticipated that on-site presentations involve even more time and cost for the preparation and conduct since venues have to be rented and presentation setups have to be created. Considering the present case study, a bus stop would need to be accessible, a fully working information system needs to be placed on-site and bus operation (e.g., by using a Wizard-of-Oz approach) needs to be involved. All these aspects would lead to an increased amount of time and cost compared to the other two presented methods.

Variability: In terms of variability, both the immersive presentation and slide-based presentation offer great advantages since the information system and potential scenarios of usage can easily be created and presented since both methods involves a digital development. This would also include potential design variants of the information system that could easily be displayed in both presentation techniques. In contrast, physical prototypes would need to be developed for the on-site presentation and the whole information system would need to be programmed to allow vivid experiences. Since every aspect to be shown needs to be developed, the variability of on-site presentations is rated lower than the comparative methods.

Interaction: Regarding the interaction of audience with the information system, all three methods show different ratings. It is anticipated that experiencing the information system first-hand in on-site presentations results in the most natural interactions. In contrast, an additional barrier is included in the MR presentation since the audience only can experience the information system via a tablet. Even though the complete information system can be experienced with this method and interaction techniques can be displayed to resemble real-life interactions, the interaction via the input device results in a less natural interaction. Since in the slide-based presentations, the audience does not have the possibility to experience the information system at all, the criterion of interaction is rated lower than the comparative methods.

Immersion: As it was mentioned before, the immersive presentation and on-site presentation both allow the audience to experience the product (i.e., information system). Furthermore, both methods allow the consideration of the application field and thus the imminent surrounding which results in an immersion while using the information system. Therefore, both presentation methods ensure immersion. In contrast, the slide-based presentation does not allow immersion and is therefore rated lower.

Effort: In terms of effort, the method of slide-based presentations involves the most advantages since the development and conduct of this method does not require specific expertise. The immersive presentation and the on-side presentation both require expertise in software development for creating the information system as well as the virtual application which increases the complexity for the involved designers. Thus, both methods are rated lower than the slide-based presentation.

Miscellaneous: Miscellaneous observations were made during the development and conduct of the immersive presentation in MR. Firstly, a range of stakeholders (i.e., designers, software developer/presenter, 3D visualizer, and one person trained in psychology) iteratively concluded on the storytelling of the presentation. Similar to the preceding research projects, the involved designer took over the coordination of the project rather than producing tasks. A major focus of the designer was to ensure a usable and self-explanatory interaction with the system through the input device (i.e., tablet). This fact and the challenge to ensure several synchronized input devices led the team to decide for the innovative input of the aforementioned cube with visual markers that the presenter has at hand during the presentation. During the qualitative data collection, participants of the presentation mentioned that the innovative method of the immersive presentation motivated curiosity and allowed first-hand experiences. During the presentation events, it became evident that it is possible for one person to host the MR presentation. Thus, it is anticipated that any person with presentation skills would be suitable for hosting the actual data collection events. In the qualitative data collection, several participants mentioned concerns regarding the usage of MR for bigger audience groups than four. Furthermore, participants mentioned after the presentation that holding the tablet throughout the whole presentation was tiring. Suggestions of including tablet stands or giving the opportunity to put the tablet aside were made afterward.

Main insights of the design study were as follows:

- The data collection of 28 participants is considered successful since the impact of MR on the presentation format could be drawn by the study setup.
- The information system was rated as 'above average' regarding its usability (collected by SUS).
- Technology acceptance of the information system in the immersive presentation group was anticipated (including perceived ease of use, perceived usefulness, attitude towards using, and behavioural intention).
- The immersive presentation supported participants to understand the product and use context.
- The advantages of the method were the possibility to immerse participants in the application field and experience the information system which led to a valid data collection. Furthermore, the digital application allowed high variability.
- During the development, the involved designer coordinated the research project and focused on the storytelling of the presentation and the usability of the interaction of participant with the input device as well as the synchronization of mentioned input devices.
- Assuming a rigorous software development, one person could take over the data collection (i.e., as presenter).

7 Answering the research questions

In the following chapter, the four previously defined research questions are answered based on the results of the data collection and comparative evaluation of the newly created VR design methods with two hypothetical design methods that are conventionally applied.

7.1 Research question 1: Which criteria are needed to evaluate and compare Virtual Reality methods and conventional design studies in a specific application domain?

The first research question deals with the definition of evaluation criteria for measuring the outcome of design studies that involve the usage of VR. The choice and usage of evaluation criteria is an advantageous approach to evaluate the outcome of design studies since it allows a direct comparison and derivation of differences based on relevant factors such as validity or time consumption (Cross, 2006; Sanders and Stappers, 2012; Stadler, Cornet and Frenkler, 2020b; Willem, 1990). As it was pointed out in chapter 4.3 Preliminary set of evaluation criteria, there is not a correct or incorrect design method to apply but “more appropriate” or “less appropriate” methods since design studies often deal with wicked problems an thus, are ill-defined (Cross, 2006; Willem, 1990). Therefore, the outcome of design studies also cannot strictly be quantified in every detail (based on Roy, 1994). To provide a framework to evaluate the impact of applying a newly created design method within a study that utilizes VR, a set of evaluation criteria was required. Within the first iteration, a preliminary set of evaluation criteria was derived from a literature review including the criteria of safety, validity, time and cost, as well as effort (cf. chapter 4.3 Preliminary set of evaluation criteria). Within the second iteration, based on expert interviews involving seven experts from industry and academia, the preliminary set of evaluation criteria was evaluated, enhanced, and based on the narratives and insights, the criteria were weighted. The refined set of evaluation criteria is as follows (cf. chapter 6.1 Expert interviews and evaluation criteria):

- Safety
- Validity
- Time and Cost
- Variability
- Interaction
- Immersion
- Effort

Firstly, it was observable that even though the majority of statements during the expert interviews had a common consensus, the experts did not all conclude on one (weighted) set of evaluation criteria but had different opinions on the relevance of criteria and their importance within a project. It is anticipated that this effect results from the different expertise of experts as well as the different application fields in which the experts utilized VR. As the range of design studies in the present dissertation show, the set of evaluation criteria that was defined in this dissertation was applicable in the domain of autonomous mobility and associated infrastructure even though not all evaluation criteria were relevant for each study. For instance, the criterion of safety was only applicable to the method of usability testing in VR since alternative methods such as Wizard-of-Oz would have exposed participants to real approaching cars which leads to potential safety hazards. For the other methods however, the criterion of safety was not relevant. This insight led to the implication that the set of evaluation criteria constantly needs to be reframed and redefined and cannot be generalized into a set of general heuristics or “rules of thumb”. Therefore, research on defining a general set of criteria for evaluating design studies and their outcomes is unsurprisingly non-existent.

In summary, a set of evaluation criteria for the chosen application domain was derived and utilized for a qualitative comparison with two other conventional design methods. This allowed the derivation of each method’s unique set of advantages and drawbacks. Thus, the research question is considered as answered in the context of the present application field of autonomous mobility and respective infrastructure.

7.2 Research question 2: To which extent can Virtual Reality trigger behaviours with relative or absolute validity compared to experiences in real-life?

The aim of this research question was to gain insights if behaviours of participants in VR are (relatively or absolutely) comparable to behaviours in real-life conditions to assess the suitability of VR as data collection tool involving human behaviours. The term “relatively” in this context means that behaviours in real-life and VR measured with physiological sensors might not result in the same amplitude but still show same tendencies in terms of order and direction of measures. As the results in chapter 6.2 Benchmark study showed, the observations of behaviours in VR, the walking speeds, as well as the narratives of participants indicate that VR has the potential to trigger behaviours close to real-life behaviours in the chosen application domain. It became evident that especially participants with no or low gaming experience stated that the VR experience felt real (Stadler, Cornet and Frenkler, 2019b). This insight corroborates with findings related to behavioural differences between gamers and non-gamers (Geslin, Bouchard, Richir, 2011; Kirschner and Williams, 2014). Geslin, Bouchard, and Richir (2011) explained that gamers showed less awareness of emotions in the chosen virtual environment and concluded on a lower psychological involvement from gamers into the virtual environment. The reason of the different behaviours in VR may result from an “inhibition of emotional response” as soon as the participant has a knowledge of the virtual environment (Geslin, Bouchard, and Richir, 2011). Depending on the purpose of the VR immersion, this fact may impact the results since participants do not behave in VR as they would do in real-life. In the present benchmark study, the VR experiment has been created with the case study of testing HMI systems on AVs for communication with pedestrians. If gamers are dissociating themselves from the immersion, they may not interact with the AV as they would do outside VR. Pizzi *et al.* (2019) compared perceptions and orientations of consumers in a virtual and physical shopping store. Despite decreased satisfaction levels, the authors conclude that behaviours in the VR-based and physical stores compare well which supports the findings of the benchmark study (Stadler, Cornet and Frenkler, 2019b). Findings of Kuliga *et al.* (2015) who investigated user experience in a real building and a corresponding virtual model also concludes that there were no significant differences between ratings of user experience in the real building and virtual model and that VR has a strong potential to be used as empirical research tool. These findings support the insights of the benchmark study.

One limitation of the study was the too small sample size, which may have hindered a generalization of results. A further limitation is the degree to which the participants were biased prior to the VR experiment. Since all participants worked as researchers in the field of autonomous transportation, their general attitude towards AVs was found to be very positive prior to the VR experiment, possibly as unconscious justification of their daily work purposes. It is anticipated that unbiased participants would have in average more neutral attitudes towards AVs and the impact on them could be investigated without bias, thus warranting further investigations.

To conclude on the present research question, it is anticipated that for the chosen application field of autonomous mobility and associated infrastructure, VR has the potential to trigger authentic behaviours from participants. As the aforementioned related research suggests, authentic behaviours in VR can also be obtained in other application domains. However, research in further application fields needs to be conducted to derive schemes of application domains in which VR would be suitable as valid research tool.

A key learning of the present benchmark study is the fact that gamers show potentially less authentic behaviours (Stadler, Cornet and Frenkler, 2019b). To compensate this fact, recruitment criteria and participant screenings could be implemented in behavioural studies to minimize the fact of distorted results caused by the involvement of too many gamers.

7.3 Research question 3: What influence does Virtual Reality have on design studies and the design process?

The aim of this research question was to derive insights on influences that the usage of VR could have on design studies including the design process. The design studies in which the methods of immersive heuristic evaluation, immersive prototyping, and MR presentation were applied involved control studies in which conventional design methods were used as control data collection tool. Thus, a direct comparison regarding the impact of VR on these respective design studies could be drawn. Even though, no control studies were conducted for the immersive survey as well as the usability testing in VR related work of researchers who used comparative design methods was consulted. As the evaluations showed, the usage of the VR during every design study had an impact on the collected data as well as the design process itself. The reflection on the impact that VR made was structured by means of the design process consensus model (chapter 4.1 A consensus model for the design process). The reflection on the impact of VR on the design process is exclusively based on the conducted design studies and thus cannot be generalized since the convergent and divergent thinking as well as the timeframe is highly dependent on the choice of each respective design method.

Research and Analysis

During the first stage of the design process, the method of immersive heuristic evaluation was created and applied to identify problems with existing guidance systems at transit hubs in an era of autonomous public transport. This newly created design method was later compared to a desktop-based heuristic evaluation (abstract nature) and on-site experiments (tangible nature). Firstly, the direct comparison to the desktop-based heuristic evaluation has proven that the usage of VR led to enhanced insights since more minor and severe usability flaws could be identified thanks to VR compared to the conventional method (cf. Appendix B). On the one hand, this suggests that divergent thinking (i.e., gaining insights) is fostered due to VR. On the other hand, this means that due to the enhanced data collection, assumptions that later would turn out to be false or ineffective could be ruled out early. These insights indicate great impacts on the subsequent stages of the design process since all further steps are based on the problem identification. In Figure 50, the impact of VR on the design process during the first stage is visualized as the area filled with blue, indicating an enhanced divergent thinking as well as the potential to rule out irrelevant insights early. As it was mentioned in chapter 4.1 A consensus model of the design process, the representation of the consensus model is of schematic nature, thus the width of the blue indicator exclusively visualizes a direction rather than a fixed value. This also applies to the subsequent visualizations (from Figure 50 to Figure 54).

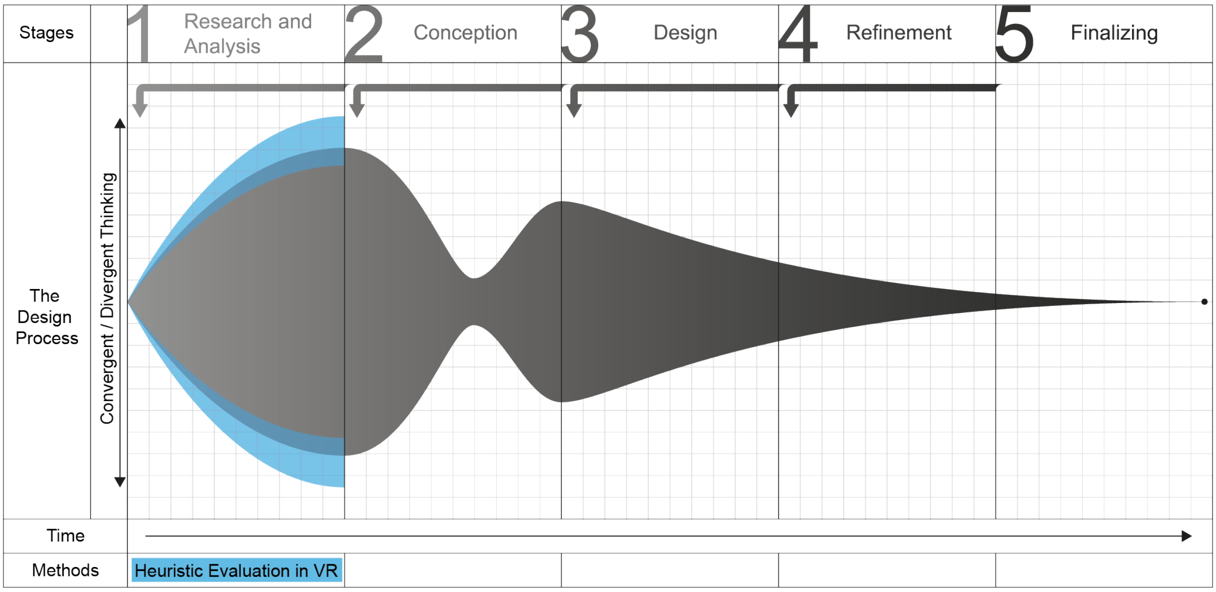


Figure 50. Virtual design process – Research and Analysis

Besides the fact that the usage of heuristic evaluation was already verified as a cost- and time-efficient method (Jeffries et al., 1991; Nielsen and Molich, 1990), other researchers already concluded that VR can save time and cost, however, mostly in later stages of the design process in which the technology was used to evaluate products (Deb, Carruth, et al., 2017; Pillai, 2017; Stadler, Cornet, Novaes Theoto, et al., 2019). A few researchers suggest that the usage of VR in early stages of the design process can increase creativity (de Groot, 2017; Rieuf and Bouchard, 2017; Yang et al., 2018). Overall, in early stages of the design process the usage of VR is currently sparse and further research is needed (Rieuf and Bouchard, 2017; Stadler et al., 2020).

Conception

During the second stage of the design process, the method of immersive surveys was created and utilized as a participatory design approach to generate concepts of public waiting rooms. This method was later compared to the methods of digital survey (abstract nature) and on-site observation (tangible nature). Firstly, the data collection gave insights in terms of user needs that were on the one hand expressed through the interactive configurator (e.g., if a participant states that the crowd level should be low this means that there is not sufficient space available) and on the other hand through the qualitative interviews after the data collection. These insights were supportive to understand underlying problems and build a design synthesis. Secondly, the usage of VR fostered the creation of design concepts. The collected data of overall 463 participants from three countries led to the derivation of design schemes that later could be translated to three promising design concepts that were further processed. During the data collection, it was observable that the usage of VR made people curious and thus led to increased motivation to participate. No positive effect on time- and cost- efficiency was measured by using the present method during the second phase of the design process. The impacts on the second stage of the design process are displayed in Figure 51. Virtual design process – Conception as the blue area that allows an enhanced convergent thinking and more sharply defined design synthesis as well as increased divergent thinking during the creation of design concepts.

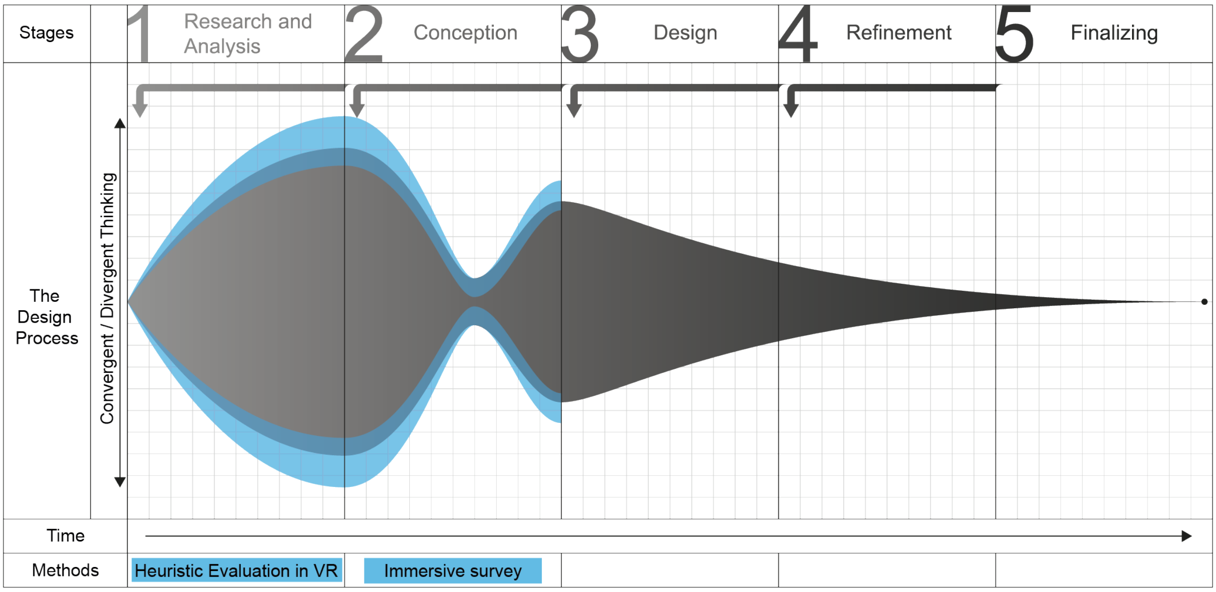


Figure 51. Virtual design process – Conception

The greatest impact that became observable during this process stage was the collection of actual preferences rather than stated preferences due to the possibility to verify selections in VR before the submission. This later could be translated into a design synthesis that was not influenced by hypothetical assumptions but verified preferences that reflected user needs. Other researchers already concluded that the collection of preferences of participants based on (immersive) experiences turned out to be more accurate than preferences based on assumptions and imagination (Farooq et al., 2018; List and Gallet, 2001; Murphy et al., 2003) (cf. 9.1.2 Immersive large-scale surveys) . Hence, compared to data collection methods that rely on stated preferences, such as digital surveys, the usage of VR leads to the derivation of more accurate user preferences as well as design concepts.

Design

During the third stage of the design process, the method of immersive prototyping was developed and utilized to create low-complexity volume models in VR. This method was later compared to the methods of desktop-based CAD (abstract nature) and high-fidelity prototyping (tangible nature). The greatest impact of this method on the design process that became observable was the fact that the creation of volume models could be conducted in an immersive environment with the potential to display the real scale of the product. This insight suggests a direct and imminent verification of the product while being developed since the designer can experience it in the actual application field. As the results show, the model quality as well as the time to develop the models showed advantages compared to the other design methods. A further fact is that the usage of VR led to excitement and an increased emotional component during the usage. It is anticipated that these facts are beneficial for the convergent work of defining the respective product properties (visualized as blue area in Figure 52).

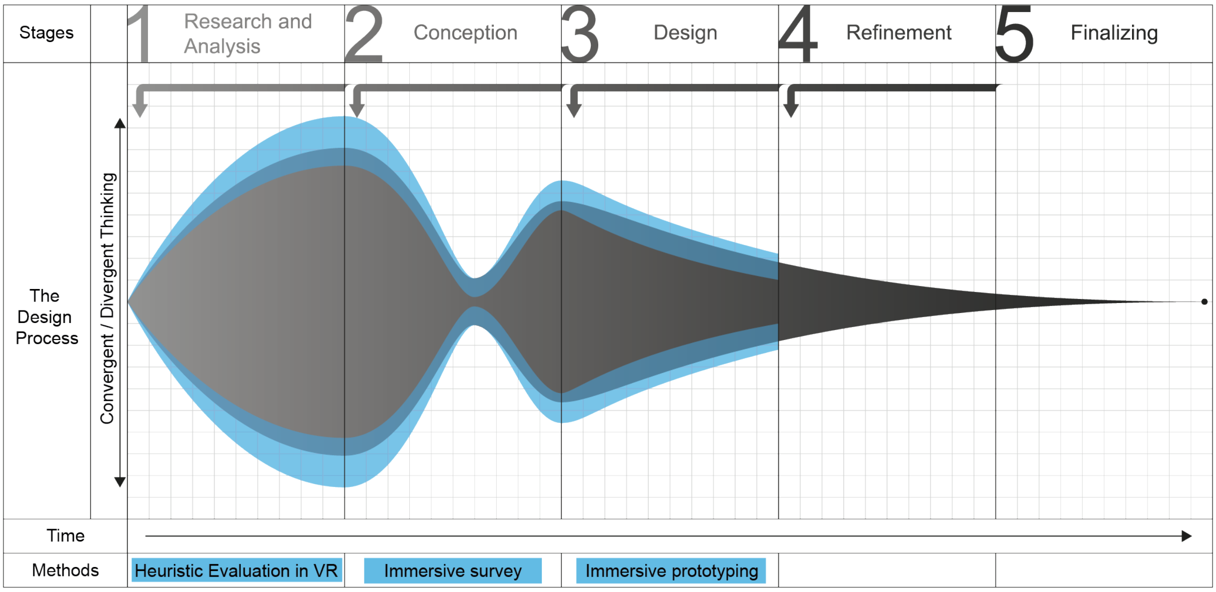


Figure 52. Virtual design process – Design

Other researchers concluded on the advantages regarding the display of scale in VR, the potential time efficiency as well as the increased emotional component of using VR for modelling (Keeley, 2018; Rieuf and Bouchard, 2017). Nevertheless, these advantages currently only apply to low-complexity models. As it was pointed out in chapter 6.5.3 Evaluation of the method, the lack of accuracy is currently a key limitation of using VR for CAD prototyping. Thus, it can be assumed that if the design study involves the development of a product with higher complexity than the present case study, the usage of VR could be insufficient and additional desktop-based prototyping becomes necessary. This is symbolized as the decreased convergence of the blue area in Figure 52 that could be caused by the sole usage of VR as CAD development tool. However, the necessity of using desktop-based CAD applications within a project does not necessary exclude the usage of VR but both could be used in a symbiotic manner. A model could be developed on screen and iteratively be reviewed in VR for immersive experiences in the application field including 1:1 scale.

Refinement

During the fourth stage of the design process, the method of usability testing in VR was developed and utilized to evaluate communication concepts from AVs to pedestrians with the intention to cross a zebra crossing. This method was later compared to the methods of structured questionnaires (abstract nature) and Wizard-of-Oz (tangible nature). The greatest impact on the design process that could be derived from this study is twofold. Firstly, valid data can be obtained due to the usage of immersive VR since authentic behaviours can be collected in a controlled environment while interacting with a system (cf. chapter 7.2 Research question 2: To which extent can Virtual Reality trigger behaviours with relative or absolute validity compared to experiences in real-life?). And secondly, since the experimental setup in VR only relies on VR hardware and a sufficiently spaced data collection venue, time- and cost-efficiency is ensured. These facts support convergence during the process stage of *Refinement*, displayed as the blue area in the process stage three in Figure 53.

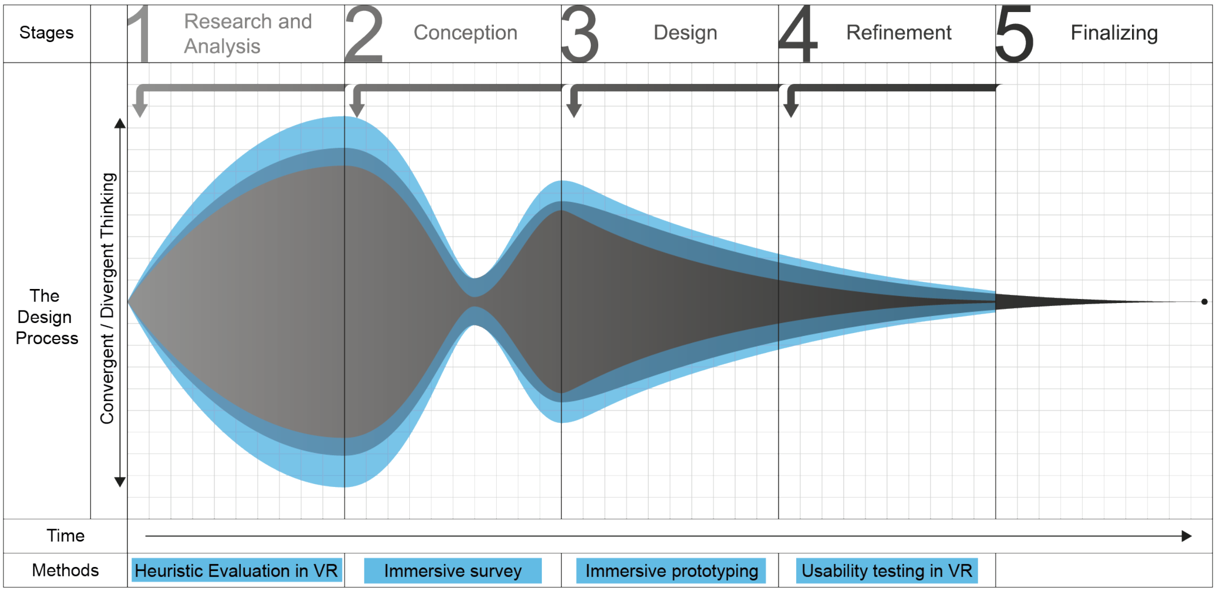


Figure 53. Virtual design process – Refinement

These findings are consistent with research of using VR in pedestrian research that concludes that VR is a suitable tool for evaluating HMI concepts for AVs and involves advantages such as time- and cost- efficiency (Deb, Carruth, et al., 2017; Pillai, 2017; Stadler, Cornet and Frenkler, 2019a). It is anticipated that the two discussed impacts of the usage of VR on the *Refinement* stage of the design process only apply if the evaluation does not involve the necessity of haptic feedback. This limitation is displayed as the decreased convergence during the phase since physical prototyping would be necessary in that case regardless of the usage of VR (Figure 53). Similar to the previously defined process stage, the usage of VR does not exclude the usage of prototypes for evaluations though but can be considered as a symbiotic strategy of product- and interaction- evaluations.

Finalizing

During the fifth and final stage of the design process, the method of MR presentation was created and utilized to measure the impact that the technology of MR can have on product presentations with a case study on displaying an information system at a bus stop that is served by autonomous busses. This method was later compared to the methods of slide-based presentations (abstract nature) and on-site presentations (tangible nature). The greatest impact on the design process that became visible is twofold. Firstly, the interactive and immersive method in MR resulted in increased perceived usability of the presented information system which constitutes an enhanced selling point. Secondly, the analysis resulted in an increased intention to use, perceived usefulness and thus technology acceptance of the presented information system. Hence, it is anticipated that using MR for presentations can increase the conviction of (potential) customers and support a successful market entry. In Figure 54, the blue circle in the *Finalizing* stage schematically symbolizes the positive impact the newly created design method can have on product presentations.

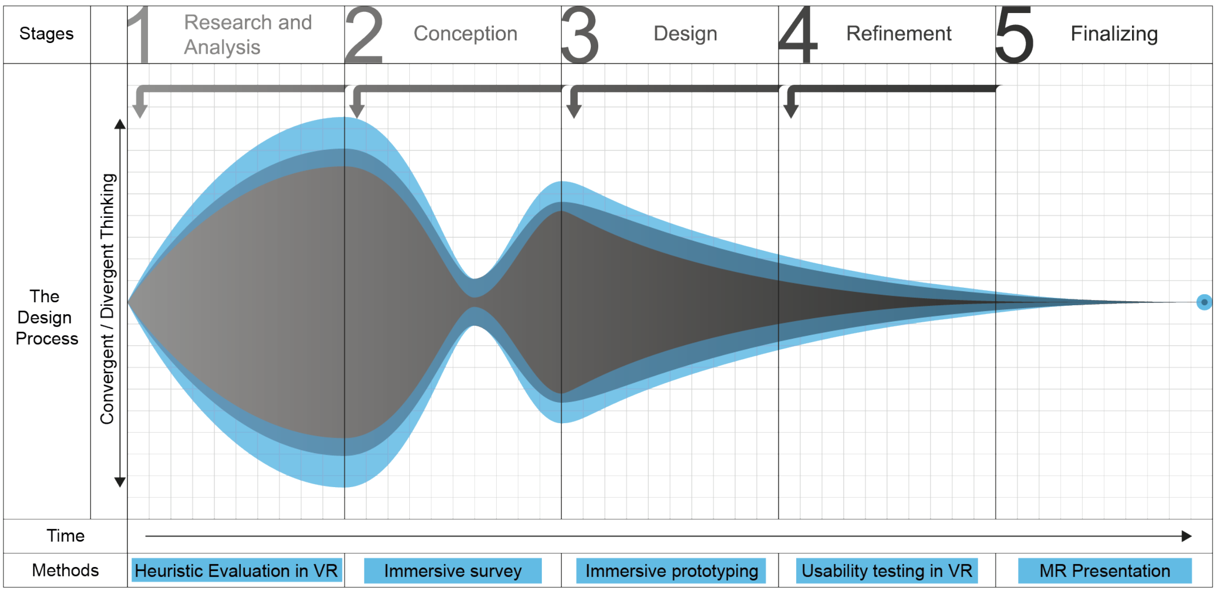


Figure 54. Virtual design process – Finalizing

Ottosson (2002) argues that VR and AR offer great advantages as communication tool in the selling of turn-key products, especially when these products are not produced yet. It is anticipated that due to the similarity of VR and AR to MR, these implications can be transferred to the usage of MR as well. XR has been sparsely used as tool for presentation and communication purposes, though (Ottosson, 2002; Zarraonandia *et al.*, 2014;

Erath *et al.*, 2017), however the present case study underlines the potential impact that this method can have on the design process (cf. 9.1.5 Immersive product presentation). Similar as for the two preceding design stages, the absence of haptic feedback could constitute a challenge. Hence, if products are presented that rely on ergonomic properties, the usage of XR should be considered more as an enhancement rather than a replacement.

Participatory activities in design studies

The present investigations have shown that VR is suitable for participatory activities within design studies. The profession of design is undergoing a continuous change. While designers started as creators to define aesthetics in the 1950ies, nowadays the profession as industrial designer is exponentially more complex (Schneorson et al., 2019; Valtonen, 2005). One successful trend in design foresees the involvement of people and potential users into the whole design process (participatory design) or in single activities (co-creation) (Abley, 2000; Bann, 2002; Murphy et al., 2003; O'Haire et al., 2011; Prahalad and Ramaswamy, 2004; Sanders and Stappers, 2008, 2014; Sanders et al., 2010). The advantages of these approaches include shared value creation, the identification of user needs, and increased efficiency. Nevertheless, these approaches involve limitations such as a lack of comprehensibility for hypothetical studies, low motivation for participation, and high involvement of time and cost (Bann, 2002; Murphy et al., 2003; O'Haire et al., 2011; Stadler, Cornet and Frenkler, 2020a). Especially considering these limitations, VR brings in great advantages, since hypothetical studies can be visualized in an immersive way, the usage of VR increases participation, and decreases the amount of time and money spent while developing and applying the respective technique.

Summary

As the aforementioned reflections on the design methods show, the usage of VR in the five presented design studies had an impact on the conducted design studies and every stage of the design process. These impacts are mostly measurable in terms of divergent and convergent thinking since the collection of data (and especially behaviours and preferences) in immersive VR can support the definition of valid and verified problems and the generation of concepts that reflect user expectations. It further allows the evaluation of concepts in virtual environments and scenarios, as well as presentation in an interactive way. Additionally, the design studies showed that the usage of VR can impact a design study's timeline, especially in the stages of *Research and Analysis* and *Refinement* (e.g., by allowing increased divergent thinking through immersive experiences and early ruling out of irrelevant or infeasible ideas). One further finding of the present investigations was the suitability of using VR for participatory activities within design studies. Ottosson (2002) investigated the usage of VR in the product development process without the focus on industrial design. His conclusions underline the potential that this new technology can have on the development process of products such as:

- VR is a useful tool to create simulations
- VR is useful to study user behaviour
- VR is useful to train personal skills
- VR is an advantageous communication tool
- VR can support aesthetic and ergonomic design

Ye *et al.* (2006) summarize that VR has the potential to generate and evaluate concepts, which confirms the conclusions drawn from three present design studies (i.e., large-scale survey, immersive prototyping, and usability testing). Pollalis and Bakos (1996) generalize in this context that the usage of technology has the potential to enhance the design process by improving efficiency, effectiveness, and quality of the developed product. Except the stated advantage of skill training (which will be discussed in chapter 9.2 Reflection on the impact of Virtual Reality on industrial design), all advantages stated by the aforementioned researchers can be confirmed. This underlines the findings of the present dissertation that make the impact of VR on design studies visible.

7.4 Research question 4: How does the usage of Virtual Reality impact the role of the designer?

The aim of the last research question was to gain insights on how the usage of VR impacts the roles of designers during design studies including activities such as problem definition, concept creation, evaluation, and presentation. The consensus on the role of the involved designers during the development of the VR application as well as the data collection throughout all design studies is as follows: During the development of the applications, the involved designers were project coordinators who interacted with other stakeholders. Further executive work was conducted in collaboration with other team members such as the definition of methodology and data analysis (incl. participant recruitment, dependent and independent variables, etc.), the development of the VR application including its interaction capabilities with participants, as well as 3D visualizations. In addition, the involved designers were responsible for the organization of the data collection events such as trade fairs and student information days.

During data collection, the designers were facilitators and guides who accompanied each participant to ensure a unique experience and successful data collection. In this way, the designers bridged the gap between non-technical versed people and technology. In addition, the involved designers were the go-to resource for participants to share their experiences and opinions after the data collection. This applies to all data collections in which participants are involved such as the immersive heuristic evaluation, immersive survey, usability testing in VR, and MR presentation. The role of the designer while applying the method of immersive prototyping during the *Design* stage did not change since designers already use prototyping during the development of products. It is anticipated though that if an immersive CAD application is used as a review tool or presentation tool that the role of the designer as presenter of a new design might get enhanced towards a facilitator who helps stakeholders to successfully understand and experience the product during the immersive design review.

Researchers such as Ehn (1993), Sanders and Stappers (2012), and Hirsch (2014) note that the role of the designers in participatory activities changes from creators and translators to facilitators and coordinators who enable people to express themselves. The reflection on the present design studies implies the same transition. From a holistic point of view, it was observable that synergies were created between the involved designers and stakeholders during each study: Firstly, the existing expertise of the interdisciplinary team during the development led to a collaborative foundation that allowed the creation of viable VR platforms for rigorous data collection. And secondly, synergies were created between the designers and participants as data collection with VR induced active participation and initiated lively dialogues. Therefore, the impact of VR on the role of the designer became evident.

8 Virtual design – A toolbox for designers

In the following chapter, the toolbox for using VR methods as industrial designer is presented. It includes design guidelines to support the decision if VR should be considered for an underlying case study and set of criteria. Furthermore, a card-set including methods that were utilized throughout the doctoral project are presented.

8.1 Design guidelines

The development and conduct of the design studies that involved the usage of VR led to a set of design guidelines, separated into guidelines during the development of the VR application and guidelines during the data collection. Since the usage of VR did not impact the stages of data analysis (compared to other digital data collection methods) no guidelines were derived from this phase.

Guidelines to be considered during the development of a VR application for data collection:

1. **Ensure the availability of required expertise in the development team.** The availability of required expertise in the development team was essential in all five design studies since the involved designers were dependent on development skills from the software developers as well as input of the 3D visualizers. This shows the limitation of current accessibility of VR development to designers who cannot take over the development alone.
2. **Ensure a continuous dialogue within the team through frequent development meetings.** A continuous dialogue between all members of the development team was crucial during the development of all five design studies since it prevented miscommunication and fostered progress. In this context, the role of the involved designers as active coordinators was observable. Agile methods fostered these continuous dialogues.
3. **Prioritize interactivity over representation. It is more important to ensure a usable application than visually appealing or realistic content.** Especially during the development of the immersive survey, it became apparent that usable interaction especially for tech-averse participants had to be prioritized over visual appeals of the VR application such as the realistic resemblance of a transit hub or the details and textures of the agents that were implemented. This fact shows the importance of usability especially in regard to people without prior experience with VR and gaming.

4. **Choose interaction techniques with the VR application based on the aimed participants' estimated skill levels (e.g., exciting enough for tech-savvy participants but not overwhelming for non-tech-affine people).** Especially for the large-scale survey and the heuristic evaluation, it became apparent that the modes of interactions such as locomotion and making selections had to be developed in regard to the participants' estimated skill level to ensure successful experiences and thus, data collections. The same aspect also applies to the interactivity of the VR application.
5. **Avoid the implementation of aspects that would lead to the exposure of technical limitations of VR (e.g., limited resolution) since it could bias participants.** Especially during the iterative development of the VR application for the usability test and the heuristic evaluation that included regular tests of the VR application inside the development team, it became clear that technical limitations needed to be prevented from exposure during the conduct of experiments. This applied for instance for the size of communication cues that could not be displayed correctly by the decreased resolution of the HMD.

Guidelines to be considered during data collection:

6. **One facilitator should be present for each HMD that is used to ensure guidance for every participant. Each facilitator needs to possess sufficient knowledge about the used hardware, the VR application with its interaction techniques, as well as the study context.** Especially during the immersive survey, in which up to three participants underwent data collection at once, it became observable that one researcher (facilitator) alone was not able to facilitate multiple participants at once but for every available HMD at least one researcher was required. Furthermore, due to ad-hoc questions of participants regarding the VR hardware and application, its interaction methods or progress of the VR experience, the involved facilitators required sufficient knowledge to be able to answer participants' questions to ensure a successful data collection.
7. **Precautions to comfort participants in case of simulator- and/or motion sickness should be taken.** Moreover, all facilitators were trained to deal with participants with emerging motion sickness or simulator sickness. Even though this fact was relevant for all data collections, especially for data collection events performed at an unknown venue additional attention was necessary to establish a comforting area and having required items such as bottled water at hand.

8. **Ensure privacy for every participant for the data collection (i.e., a quiet space). Avoid to openly stream the participant's first-person view to other people.** Especially during the data collection of the immersive survey, which was performed among others at trade fairs and university information days, it became observable that noise from the environment can reduce immersion and distract participants while undergoing the data collection. Thus, the data collections were carried out in spaces as quiet as possible to avoid any distractions for participants. Furthermore, it was anticipated that public streaming of the first-person view of participants in VR could discourage passer-by to spontaneously participate in the study.
9. **Establish context: By ensuring holistic experiences in VR, participants fully understand the study context to build an opinion on it.** The establishment of context was important during all data collection events but especially when there was a chance of passer-by participating ad-hoc. It is anticipated that this was due to the fact that people wanted to know what to expect, what kind of data is collected and decide to participate based on that introduction. Furthermore, it became evident that people started to actively think about the topic of the study when the study context was provided resulting in a holistic experience to them. This led to informal conversations between participants and facilitators but also participants who were strangers to one another.

8.2 Method cards

For each VR design method that was developed and applied, one method card was created. Each card represents one method and explains its usage. Additionally, one introduction card briefly explains the usage of the method cards as well as the meanings of the icons placed in the lower part of the method cards (Figure 55 – Figure 60).

Introduction Card

The Virtual Design Method Cards describe design methods in which Virtual Reality is utilized. Each method card consists of three categories, firstly when the VR method could be used, followed by specifics to the method and lastly considerations. Below the descriptions, icons symbolize further characteristics. When an icon is highlighted in colour, the specific is suitable for the respective method. The icons are as follows:

1	2	3	4	5

- Representation of the design process stages
- Highlighted tiles indicate a suitability of the method for the respective process stage (i.e., above: stage one and three)

6 DoF
3 DoF

- Highlighted “6 DoF” indicates the suitability of the present method for devices with six degrees of freedom
- Highlighted “3 DoF” indicates the suitability of the present method for devices with three degrees of freedom

- Highlighted symbols indicate the suitability of specific locomotion techniques for the present method
- From left to right: Arm-swinging, physical walking, touchpad movement, and teleportation

E LU U

- Highlighted characters indicate the suitability for the involvement of different user groups
- E = Experts; LU = Lead-users; U = Users

- Highlighted bars indicate suitable study scales
- Left bar highlighted: Small-scale study
- Middle bar highlighted: Middle-scale study
- Right bar highlighted: Large-scale study

Figure 55. Introduction Card

Immersive Heuristic Evaluation

When to use:

- Data collection is not suitable/possible in laboratory conditions
- Prototypes are too complex/expensive for manufacturing
- Prototypes are not feasible
- Data collection is dangerous for participants
- A product is evaluated in an environment that is not accessible

Specifics of implementation:

- Follow the conventional approaches for heuristic evaluations
- Create an immersive environment in which your product is tested
- Include suitable interaction- and locomotion- techniques
- Implement scenarios that allow the evaluation of the product in a range of situations
- During the testings: Let the experts familiarize with the technology before the evaluation starts

Considerations:

- Adapt heuristics to be suitable for the chosen case study
- Include additional modes such as filters that simulate characteristics of vulnerable user (e.g., occlusion filter)
- Follow a think aloud prinicple for immersed experts
- Consider to group the participants into pairs to allow a seamless documentation of experiences

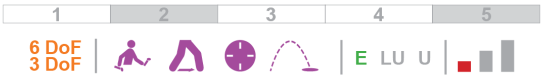


Figure 56. Method card: Immersive Heuristic Evaluation

Immersive Survey

When to use:

- A product is evaluated in an environment that is not accessible
- The data collection involves a high amount of data (e.g., including more than ~30 study items)
- Immersion is required for valid data collection
- Data collection is dangerous for participants

Specifics of implementation:

- Create an immersive environment in which the product is tested
- Include suitable interaction- and locomotion- techniques
- Implement interactive and immersive scenes into the environment (i.e., selection items of the survey)
- Provide a tutorial to the participants outside of VR
- During the data collection, follow a standardized procedure for every participant to increase comparability or results

Considerations:

- Respect the estimated technology skill level of the participants
- Include multiple choice questionnaires and background surveys directly in the VR application
- Use screen mirroring: Facilitators can address participants' problems during the data collection more easily

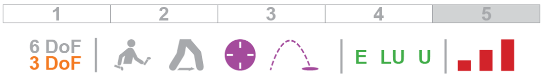


Figure 57. Method card: Immersive Survey

Immersive Prototyping

When to use:

- Physical prototypes are not feasible or affordable
- Short timeframe
- Real-scale experiences are needed
- Design reviews in hypothetical scenarios are needed
- No precision prototyping is needed

Specifics of implementation:

- Create an immersive prototyping application that includes necessary functionality, alternatively:
- Utilize an open source immersive prototyping application such as ImPro
- Ensure that the chosen application offers the needed tools, otherwise add them to the applications
- Regularly review the prototype in the immersive environment

Considerations:

- 6 DoF offers better workflow than 3 DoF
- By implementing scenes, the product can be reviewed in its actual application domain(s)
- For high-precision prototyping, immersive prototyping applications should be combined with desktop-based CAD applications

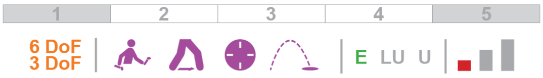


Figure 58. Method card: Immersive Prototyping

Usability Testing in VR

When to use:

- Conventional testings involve safety hazards for participants
- Prototypes are too complex/expensive for manufacturing
- Prototypes are not feasible
- Tests in hypothetical scenarios are required
- *In situ* observations are required while maintaining laboratorial conditions

Specifics of implementation:

- Follow approaches for conventional usability testings
- Create an immersive environment including the application domain and the product to be tested
- Include suitable interaction- and locomotion- techniques
- Let participants familiarize with VR before starting the test
- Collect quantitative and qualitative data while participants interact withe the product (e.g., walking speeds, cognitive efforts)

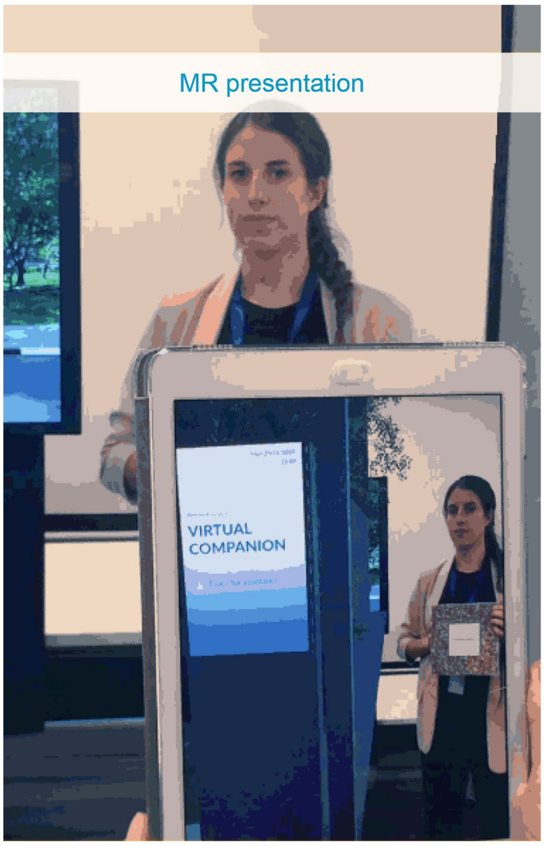
Considerations:

- When participants need to move while interacting with the product, consider the locomotion techniques arm-swinging and physical walking
- Physiological sensors allow the derivation of participants' stress level while interacting with the product
- Include background questionnaires directly in the VR application
- Include several scenarios and tasks to evaluate the product in different application contexts

1 2 3 4 5

6 DoF
3 DoF | E LU U |

Figure 59. Method card: Usability Testing in VR



MR Presentation

When to use:

- Present products in an immersive and collaborative way
- Present products whose deployment lies in the future
- Present digital products
- Present products in several application fields
- Allow interactive presentations
- Conduct remote or hybrid presentations

Specifics of implementation:

- Clarify the presentation venue and plan the usage of MR for it
- Build an MR environment and decide for a technology to display it
- Implement the product to be presented as well as its application field
- Plan the interplay of product, surrounding, presenter, and audience
- Include interactivity to allow the audience to experience the product
- Include visual triggers to synchronize the MR devices and manage the presentation narrative

Considerations:

- Smartphones, tablets, and Head-Mounted Displays are suitable for MR
- The audience should be able to put the MR devices aside
- For business presentations: Not everyone is willing to wear head-mounted devices
- Not all participants are open to MR, consider a presentation format that also works without MR

1 2 3 4 5

6 DoF
3 DoF | E LU U

Figure 60. Method card: MR Presentation[5]

[5] Disclaimer: The usage of this picture was granted by the depicted person

9 Discussion

In the present chapter, the results of each of the aforementioned case studies are interpreted, followed by reflection on the impact of Virtual Reality on industrial design on four different levels.

9.1 Case study discussion

9.1.1 Immersive heuristic evaluation

Jeffries *et al.* (1991) describe the method of heuristic evaluation as an inexpensive evaluation method that offers efficiency in terms of identifying usability flaws. By comparing the other methods such as on-site experiments, it becomes evident that the (immersive) digital simulation of a use case has the potential to save cost and time. Furthermore, the comparison of the immersive heuristic evaluation with the conventional method shows that VR even has the potential to derive more usability flaws than the desktop-based method. Nielsen and Molich (1990) also stated that the major advantages of heuristic evaluation are cost-effectiveness, the intuitive procedure, no need for advanced planning, and the fact that the method can be used in the early phases of the development process. This is consistent with the finding of chapter 6.3 Immersive heuristic evaluation since the comparative analysis showed that the usage of VR for evaluating guidance systems involved the most advantages compared to the other design methods.

However, the usage of the immersive heuristic evaluation involved technical limitations as well: Firstly, the experts stated that spending too much time in VR could lead to nausea. In addition, it was discovered that watching the first-person view on a screen as second expert (i.e., outside VR) could lead to nausea even though not being directly immersed in VR. Secondly, the touchpad locomotion technique was not well received by the experts since the sensitivity was set too high, causing the movements to appear less realistic than the other locomotion techniques. Lastly, the experts noticed that by displaying a very high amount of crowd simulation agents in the virtual environment, the performance of the VR application decreased. Since the frame rate of the VR application is affected by this, the risk of nausea could be increased (LaViola, 2000).

A range of implications can be drawn from this design study. Firstly, the immersive heuristic evaluation can be advantageous over conventional desktop-based heuristic evaluation as well as on-side experiments since it enables the collection of valid data while being a cost- and time-efficient method with high variability and immersion. Especially for the chosen case study, the qualitative assessment shows that a simulation could be preferable over a physical environment which could lead to a paradigm shift in design studies. Secondly, new possibilities are open to explore due to the immersive simulation as the occlusion filter showed. The usage of filters and simulation to experience a system out of the perspective of vulnerable users is a key advantage for HCD approaches that can lead to more profound findings and solutions for wicked problems.

9.1.2 Immersive large-scale surveys

In the present design study, a large-scale survey was developed and conducted to collect people’s preferences on public waiting rooms based on an immersive experience in VR involving people with different backgrounds in terms of age, place of living, and prior experience with VR. The main insights of the present design study are threefold: Firstly, it was observable that the unique and immersive experience resulted in a better understanding of the study context for the participants and allowed the participants to verify to which extent their configuration matched their preferences before submission. Therefore, VR could bridge the gap between stated preferences and actual preferences. Researchers such as Farooq, Cherchi and Sobhani (2018), Murphy *et al.* (2003), and List and Gallet (2001) conclude in that context that preferences based on experiences are more accurate, while preferences based on hypothetical estimations can lead to discrepancies when the actual needs and desires of participants are taken into account. Secondly, the attendance of public events as data collection platforms enabled the inclusion of participants with a wide variety of backgrounds, since data from 463 participants aged 8 to 89 years, including passers-by, families, students and seniors could be collected. This showed the potential accessibility of using VR even for participants without previous VR experience. Nevertheless, challenges for some participants and especially for seniors when interacting with the VR system became observable such as children and seniors who showed fundamental differences in their needs and the accessibility of VR. This is consistent with the findings of Gregor and Newell (2001), who conclude that designers need to move away from thinking of design for "typical users" and consider inclusive design.

Billis *et al.* (2010) list guidelines for improving accessibility for seniors to use VR applications. These guidelines include aspects such as sufficient object and letter size, simple interfaces, and sufficient guidance. Similar phenomena were observable in the present design study, especially with regard to the simplicity of user interfaces and the necessary guidance for seniors. Thirdly, design guidelines for the development and conduct of a study to collect people's preferences in VR could be defined. These guidelines showed similarities to the guidelines by Carlsson and Sonesson (2017) for the development of VR user experience studies in vehicles, which also emphasize the technology of VR and the interactivity of the application. Furthermore, parallels were found to the premises of Sanders and Simons (2009) in the context of co-creation to establish diversity of participants, continuous dialogues, and holistic experiences.

Regarding the limitations of the VR platform, the usability of the application offers room for improvement. Although an attempt was made to make interaction in VR as easy as possible, it became apparent that people without previous experience with VR (often seniors) tended to have problems when interacting with the system. Another limitation was the guidance of the involved designers throughout the data collection. Since the designers accompanied each participant to ensure a successful experience in VR, the comparability of the collected data decreased since the data collection procedure was not fully standardized from participant to participant. It is assumed that this may have had an impact on the collected data. Future studies could investigate how standardization could be established while participants can have guided and unique experiences in VR. In addition, the platform will be applied to other application areas to prove its transferability (e.g., the collection of preferences of people who regularly use public transport like metro or bus).

A range of implications can be drawn from this design study. Firstly, it became evident that the usage of VR for immersive survey to collect people's preferences has its strength in the validity of results and immersion that allows the verification of selection possibilities. Secondly, the design study showed that VR can be a suitable tool to conduct large-scale studies in VR. The whole study procedure from consent agreement over questionnaires and actual data collection can be included in the application which results in a centralized and digital documentation. This factor makes the analysis of collected data more efficient. The study showed the potential that users mostly are able to pass through the whole experience by themselves. This could revolutionize the way data collection could be conducted in the future as people could be recruited to participate from home while still having the possibility to experience immersive environments (provided the fact that VR devices are widely distributed for end users). Nevertheless, the skill level of the considered participants as well as their accessibility to technology is a key consideration since it defines the possible interaction of the application.

9.1.3 Immersive prototyping

In the present design study, VR was used for developing low-complexity 3D models in an immersive environment with a focus on usability and functionality which are fundamental for industrial designers while creating volume models. The results of the present design study were insightful as it became evident that the usage of VR involves advantages over desktop-based CAD applications in terms of usability, functionality, and quality of generated 3D models.

This could be particularly beneficial for product development, as it shows that VR offers even more possibilities to create 3D models for decision making in design reviews (e.g., for discussing product details in early phases of CAD development in an immersive environment). The analysis of applications helped to identify aspects such as tool visibility and a clear user interface that increases and decreases the usability of the respective commercial application, which led to the design guidelines for the development of immersive prototyping applications. It is anticipated that this comparison and the development of the design guidelines have the capability to provide a basic framework to support further research on VR CAD applications and facilitate potential transferability to other application fields. Finally, the general comparison of desktop-based CAD applications and VR CAD applications showed the impact of VR on the time required to develop a low-complexity model, on the functionality and usability, and on the quality of the models. This comparison showed that VR has a great potential to improve product development. The user ratings and the qualitative assessment showed that the participants were enthusiastic about using VR for prototyping. This reflects the findings of Rieuf and Bouchard (2017), who concluded that the use of VR in early stages of design can enhance the emotional component of the activity and lead to a higher overall commitment of the involved designers to the task at hand. Moreover, during and after the test, participants expressed positive opinions about possibility to experience the scale of the 3D models, the ability to view the model from any perspective, and the intuitive and unique interaction to create 3D models. This was reflected in the model quality, which showed that the proportions and assembly of the created models were better when using VR applications. This is consistent with the results of Keeley (2018), who conducted an experiment on sketching in VR. The results showed that participants had a greater sense of scale and perspective when using the immersive technology.

Although visual guides were implemented, the lack of accuracy was still the greatest limitation of using VR for immersive prototyping in the present design study. The majority of participants stated that immersive prototyping does not provide high accuracy compared to desktop-based CAD applications, which could potentially affect the model quality. Furthermore, due to the simplicity of the task, only implications can be anticipated for using VR for design activities. Additional evaluations including more complex tasks are required. Arora *et al.* (2017) concluded that the lack of precision and accuracy is a key limitation in the use of VR. Further research is planned to improve accuracy for immersive prototyping (based on Stadler *et al.*, 2020).

A range of implications can be drawn from this design study. The aspect of immersion allows designers to experience models in real scale and in any desired environment. This possibility could lead to the decrease or even disappearance of certain iterations of physical prototypes if the VR design tool is validated (e.g., in terms of materials, reflections, shadow gaps, etc.). This retrospectively could further accelerate product development processes and decrease costs for complex prototyping. Furthermore, the present study led to the insight that prototyping in VR leads to an enriched emotional component and excitement which supports creativity during the product development. Hence, the technology of VR could become a tool to foster creativity and modern problem-solving for industrial designers. Lastly, the digital factor of the VR application and the potential to share the virtual space implies new possibilities of remote CAD development and design reviews.

9.1.4 Usability testing in VR

In the present design study, VR was used to conduct usability tests to evaluate explicit HMIs for the communication from AVs to pedestrians in ambiguous situations such as a zebra crossing. Furthermore, it was aimed to evaluate a range of display-based and projector-based HMI concepts in terms of efficiency, effectiveness, and satisfaction. Due to the ease of developing and visualising communication cues in VR, the method turned out to be a flexible and efficient technique in terms of cost and time for conducting usability tests in the application domain of autonomous mobility. The data collections showed that the usage of VR for evaluating communication cues was a suitable tool, since it allowed the researchers to expose the participants to the traffic situation and confront them with the explicit HMI concepts. By comparing the HMI concepts to the control scenario, the direct impact of the communication cues on the performance of the participants was made clear. This shows that the technology of VR constitutes a suitable tool for behavioural research in the application field of autonomous mobility. This insight is in line with other researchers who utilized the technology of VR for pedestrian research (Deb, Carruth, *et al.*, 2017; Pillai, 2017). In comparison to other design methods, by using VR designers have the possibility to observe people while interacting with systems and products that are not yet deployed on the market. This provides the opportunity for designers to evaluate products before complex prototypes are built.

The authors focused specifically on the usability of pedestrian interaction and AVs at a zebra crossing. Therefore, two main influences were neglected within the study. Firstly, the consideration of weather- and light- conditions, and secondly, the performance of technical properties of the visualization technology. Since it is assumed that these factors have a decisive influence on the visibility of HMIs, weather simulations and improved display properties for selected technologies are planned for implementation in future studies. Furthermore, restricted field of view of the HMDs as well as insufficient resolution of the displays could have impacted the visibility of HMIs. Moreover, the focus of this study was on the evaluation of the usability attribute efficiency, effectiveness, and satisfaction to determine the general need for explicit HMI concepts and a selection of useful concepts. In future experiments, additional usability attributes such as accessibility are considered since fundamental influences are expected on usability especially for people with disabilities.

A range of implications can be drawn from this design study. Firstly, the design methods constituted a safe but valid alternative to other research methods such as desktop-based simulations and Wizard-of-Oz studies. The successful evaluation of the HMI concepts showed the potential of using VR for behavioural experiments since technology (such as the HMIs) can already be evaluated in terms of usability and acceptance even before it is mature for market implementations. More importantly, while technology is maturing, tests with involving actual participant behaviours can be conducted while ensuring highest safety standards for participants and equipment. This advantage has the potential to turn out as key advantage of using VR in research involving AVs. Secondly, as other researchers already concluded (Deb et al., 2018; Deb, Carruth, et al., 2017; Pillai, 2017), the usage of VR in the present application field involving AVs turned out to be an empirical research tool. It shows the potential of VR for being used for experiments and in scientific research.

9.1.5 Immersive product presentation

In the present design study, MR was used as tool for presenting an information system at bus stops for autonomous buses to an audience and to measure the impact the technology of MR has on perceived usability and technology acceptance. The main insights of the present design study were as follows: Firstly, the immersive presentation format showed a trend towards high perceived usability of the information system. Additionally, significant correlations between the usability of the presentation format and the perceived usability of the presented information system were observed. This indicates that the presentation method is able to influence the perceived quality of the content. Secondly, significant tendencies regarding the technology acceptance of the information system were measurable when being presented via MR. In a number of studies, XR technologies were used for communication and presentation purposes. Erath *et al.* (2017) used VR for communication and research purposes in the field of transportation research in Singapore. The researchers conclude that VR is capable of replacing conventional models by enabling enriched interactivity and communication of time and motion. Even though, in the present design study another technology in the field of XR was used, same implications could be drawn. Nevertheless, research on the integration of MR into presentations is sparse and especially its impact on usability and user acceptance remains uncertain (Trauth, 2020).

The following limitations were observed during the data collection. Firstly, the sample size for a between-subject study was rather small (N = 28). Ideally, both the MR group and the control group should have consisted of at least 30 participants. Furthermore, all recruited participants worked in the application area of the study, which could have led to biased opinions and preferences. Another limitation is the standardization of the presentations. Although the focus was on making the MR presentation and the control presentation (i.e., slide-based) as similar as possible, presentations have a dynamic character and cannot be fully controlled and standardized. This also includes the characteristics of the presenter.

As an implication, the design study indicated that MR has the capability to be used as a tool for product presentations in the business context with its strengths in variability, validity, and immersion. Beyond the possibility to guide the audience through an immersive experience, the storytelling could be improved since in contrast to slide-based presentations, XR presentation could be reactive to user feedback, behaviours, and preferences. Thus, presenters could react and focus on presentation details tailored upon the audience's interests. Extrapolating this thought, future research could focus on the acceptance and perceived usability of products when being presented in in interactive and multi-level presentation (i.e., presentations that are conceptualized in a non-linear way and are adaptive to the inputs and feedbacks of the audience).

9.1.6 Summary to the case study discussions

As the case study discussion showed, all design studies were insightful and enabled to understand how VR can be applied in a meaningful way for designers and in regard to the profession design. Beyond this fact, the research questions for each respective design study were answered and valuable contributions and implications could be drawn. However, each design study also involved a set of limitations, mostly connected to technological factors of VR, such as restricted field of view and resolution (usability testing in VR), as well as potential nausea for users being immersed in VR and for spectators following the first-person view via a screen (e.g., during the immersive heuristic evaluation). Besides that, no severe drawbacks of using VR compared to conventional design methods were observable. In contrast, as each design study showed, if applied correctly, each newly developed immersive design method has the potential to offer an individual set of advantages, mostly connect to validity of results, variability, and immersion. As the implications show, the usage of VR for the chosen case studies has great potential to further develop data collection techniques as designer and to deal with wicked problems which retrospectively constitutes an enhancement for industrial design in general. To further reflect on this aspect, the previously defined research questions will be discussed in the following subchapters.

9.2 Reflection on the impact of Virtual Reality on industrial design

This chapter aims to reflect on the impact of XR technologies and especially VR on different levels of industrial design. Before coming to the potential of using VR in industrial design, it must be mentioned that there are limitations regarding the generalizability of results as well as technical aspects in the present dissertation. The attempt to measure success in design is already body of knowledge in design research. Researchers such as Roy (1994) tried to quantify the benefits of good design, but with a focus on product success and return on investment. This means the quantification is based on products that entered the market. Additional performance indicators that were considered involved the amount of design awards, achieved by the product, citations on the British Design Council's Selection of well-designed British goods, as well as the number of times that the products or company was mentioned by competitors as leading design producers in their industrial sector. Even though this approach might be a promising attempt to quantify the impact of design on success, it falls short in measuring the impact of certain variables during the product development (such as new technologies) on the process as such. Nevertheless, one major limitation of the present reflection becomes evident following this line of thought: Due to the case study of fully autonomous vehicles in Singapore from 2030 onwards as well as the project setting in a research institute in which the focus lied on research and not the deployment of products, for all design studies there was no final product deployed that could be observed in terms of market success. Additionally, no hardware products were developed within the research institute that would have allowed a one-to-one comparison including aspects such as ergonomics, feel, and aesthetics.

To allow an assessment of the impact of VR on industrial design, the following subchapters are divided into reflections on the level of technology of VR, participants to design studies, the involved designers, design, as well as design education, followed by concluding thoughts.

Technology

On the level of technology, research and development on VR is evolving quickly. Even though VR is not a mature technology yet, its potential for industrial designers has been proven in the present dissertation. As VR develops towards becoming a mass medium, new use cases and application domains are getting identified as suitable for its utilization. The usage of VR in research has the potential on the one hand to improve the technology itself by conducting basic science but also enhance conventional methods of data collection. The obtained insights of the present dissertation might have implications on how data could be collected in the future. Experiments are conducted to verify or falsify a hypothesis with dependent and independent variables preferably in a controlled environment to reduce noises that could distort the collected results (Chalmers, 1999; Martin and Hanington, 2012; Webster Jr. and Sell, 2014; Wu and Hamada, 2009). Dependent on test setups as well as the considered variables, conducting and analysing experiments can involve a considerable amount of time, costs, and effort. Advantages of experiments lie in its validity and reliability of results. As the related work as well as the conducted benchmark study suggests, VR could become a considerable technology for conducting experiments in the future which could have a great impact on scientific efforts, provided the fact that the visualization technology of HMDs develop towards human-like field of view and resolution. Even though research is ongoing in the field of providing haptic feedback for users of VR, to this date, it remains uncertain to which extent and at which point of time realistic haptic feedback in VR can be provided. Nevertheless, if experiments do not require participants to experience haptic feedback (and maybe realistic field of view or resolution), VR already has the potential to facilitate the conduct of experiments. Therefore, on a technological level, the present dissertation leads to the implication that VR can constitute a strategic tool in the profession of industrial design for the collection of valid data.

Considering the technology of autonomous mobility, the usage of VR for the present case studies supported the definition and evaluation of concepts that become relevant once AVs are deployed. Even before level 5 AVs are feasible, with the help of VR problems could be defined in scenarios that could emerge in the future (i.e., wayfinding at transit hubs) and concepts such as HMIs for the communication between pedestrians and AVs could be evaluated. Since regulations for the deployment are yet to be defined, research in this field constitutes a key understanding for identifying necessary opportunities but also regulations. As the results and accompanying implications show, the technology of VR during data collection also has the potential to foster development of other technologies. However, successful data collection and utilization of VR is not only dependent on the technology but also on the involvement of participants.

Participants

On the level of participants, it became observable that the usage of VR had an impact on the motivation of people to participate in data collection events. It is anticipated that a considerable amount of people had the motivation to participate out of curiosity to experience the technology. Surprisingly, this did not only apply to younger generations but also seniors. In contrast, few people were intimidated by the technology. Currently, the technology could be a Pandora’s box for people who never tried it before. Furthermore, people could have wrong conceptions about VR caused by bad experiences that lie in the past (e.g., roller coaster ride with a Smartphone based VR application with insufficient frames per second). Therefore, it is essential on the one hand that the technology of VR is made transparent and understandable to participants to alleviate the fear of it. This can be achieved by explaining the fundamental functionality of VR as well as by explaining the procedure and experience that participants would be exposed to. On the other hand, the used hardware as well as the developed VR application must be suitable for the data collection. As it was explained before, on the level of hardware, this means that devices with sufficient performance need to be used to ensure a constantly high framerate to prevent motion sickness or simulator sickness. On the level of software, this means that firstly it needs to be developed in a way so that high framerates can be achieved and maintained. Secondly, the interactivity of the application must be designed to suit the expected skill level of the potential participants. These facts show that the participants need to be put in the focus for the development of the application and preparation for data collection in order to ensure successful data collections.

Furthermore, the involved designers observed that participants who were alien to one another started to exchange after conducting the tests. Thus, vivid dialogues and synergies were established between participants and designers caused by the usage of the technology of VR. The aim of the present dissertation was to establish a range of study scales and focus groups of users in the studies to see the potential of using VR in different study scales and for participants with various expertise. This included small study scales of less than 10 participants up to a large-scale study that involved over 450 participants. Additionally, focus groups divided into users, lead-users, and experts were considered in the design studies. As the results of the design studies showed, VR was successfully used with various study scales as well as with every considered focus group. Nevertheless, the usage of VR was also intimidating for some participants, especially when the technology was unknown to them. Further developments in VR and cautious preparation of VR applications with an HCD approach can counteract this fact. Moreover, the usage of VR resulted in authentic behaviours and reactions of participants. However, it became observable that participants with high prior experience in gaming showed decreased authentic behaviours. Depending on the case study, a participant screening to control the involvement of participants with high prior gaming experience should be considered.

Designer

On the level of the designer, the usage of VR throughout the design process impacted the way the involved designers worked. As interdisciplinary teams were required, the designers did not create the product anymore but collaborated with people from other disciplines and took over the role as a coordinator during the development. During the data collection, the involved designers became facilitators who ensured a unique and successful experience while bridging the gap from people to technology. This implies that the usage of VR as designer has the potential to change the way of working towards the involvement of more stakeholders such as potential users. On the one hand this implies that designers will have to possess more basic knowledge in other fields such as software development and psychology and on the other hand this means that a future core function as a designer will require to make sure that people can express their ideas and share their creativity.

As the role of the industrial designer, also the designer's skill set evolved over the last decades (Hauffe, 2008; Schneorson et al., 2019; Valtonen, 2005). While in the 1950ies, designers were seen as creators with a focus on aesthetics, the became part of a team with mechanics and marketing specialists, end-user experts, and entrepreneurs (Valtonen, 2005). While a standard skill set includes creativity, knowledge about form and function, empathy, ideation strength, manufacturing processes, as well as prototyping and testing (Schneorson et al., 2019), the future skill set is required to become more broad and interdisciplinary (Frenkler, 2020; Valtonen, 2005). Sanders and Stappers (2014) argue that design evolved in a way that in the 1980ies designers did not explore what to design but how to design what the client requested. This shifted in the 2010s towards the exploration of "what to design", not only "how to design". The authors foresee that in the 2040ies, designers will ensure the products that are designed make sense for the lives of future people. This is in line with statements of Rams (2016) and Frenkler (2020) who state that it's the designers' responsibility to ensure that useful products are developed and unnecessary products are prevented. Sanders and Stappers (2014) explain the skill sets and competencies of general designers as: problem solving of complex tasks, flexibility and adaptivity, as well as communication skills. As skill set of industrial designers, the authors mention design thinking, methodologies and processes, 2D and 3D modelling, industrial processes, and knowledge integration. Frenkler (2020) argues that designers need to understand the language of other disciplines in order to form interdisciplinary teams and closely collaborate with people with other expertise. This was reflected in the curriculum of the chair of industrial design of the Technical University of Munich, in which students had the chance to take courses in other disciplines such as Psychology and Philosophy (Frenkler, 2020; Technical University of Munich, 2020). Frenkler (2020) also summarizes this in his design formula, described in chapter 2.3 Definition of industrial design. It becomes evident that designers need to have a broad understanding of people, businesses, innovation, and manufacturing.

Even though, designers learn interdisciplinary skills through their apprenticeship, their expertise is (and should remain) focused on design (in a more or less broad way). Therefore, designers will not become psychologists, philosophers, or software developers even though they possess basic knowledge and skills in these fields. Dorta and Pérez (2006) claim in this context that the designers' skills and the design process itself must be considered when VR techniques are applied. In a world in which complex technology is advancing rapidly, it becomes evident that designers are dependent on other expertise and need to work in interdisciplinary teams to gain access to these expert skills. Thus, the importance of the synergetic way of working with other departments as described above becomes apparent. However, a basic skill set is required to understand the context as designer. Considering the usage of VR, the involved designers must understand how VR can be used for the different kinds of data collection throughout the design process, how VR applications are developed, and how data is collected with the help of VR. Hence, a sufficient understanding of the nature of VR and its ability to solve problems encountered in VR is required (based on Pollalis and Bakos, 1996). The consideration regarding the required skill set of industrial designers for using VR also needs to be reflected in the context of future design education. As it was concluded, designers do not need to become software developers, however, designers must understand the way of working as well as the language of software developers in order to define a rigorous and valid methodology as well as support the creation of a suitable VR application for doing so. Throughout all five conducted design studies, it became evident that VR has the potential to positively enhance the design process, as long as the required expertise is available. Cross (1999) stated that after the implementation of CAD, VR could become the next technical revolution to design. Thus, prospective designers should be taught the basics of software development as well as the usage of VR to an extent, that interdisciplinary work with the other departments can be conducted effectively to ensure a project's success.

Design

Extrapolating from the level of the designer, the insights of the current dissertation also leads to implications on the level of design as a profession. As technology strives towards automation and digitalization, the profession of design needs to concur. Digitalization and the introduction of CAD revolutionized the profession of design since it led to increased efficiency in terms of accuracy, improved modelling capabilities, and product quality (Stadler et al., 2020). A strong similarity to the present findings can be drawn in terms of VR. Furthermore, design researchers already foresaw the potential that VR could constitute a further paradigm shift for industrial designers in the late 1990ies (Cross, 1999). The usage of technology during design can foster innovation and allow more efficient ways of working or enhanced insights. However, especially in a technology driven world, the focus of research and product development should not lie on the technology itself but on the human and thus follow, a HCD approach (based on Niemelä *et al.*, 2014). Hence, the designers should carefully consider when it makes sense to use this technology during the design process and focus on the benefit it brings towards the identification of problems, the participatory generation of concepts, and evaluation of concepts in a save and controlled environment. VR should not be used during the design process for the sake of using it since this approach could shift the designers' mindset from an HCD towards a sole technology driven motivation. This insight also applies to the frequency of using VR during the design process. There is no value in using VR in every stage of the design process during one project for the sake of using it, but it should be considered when its impact benefits the design study the most. Lastly, the present comparative evaluation of the newly developed VR methods with conventional methods does not have the intention to exclude any other design methods from its usage. Design is an iterative process (Heufler, 2004; Hirsch, 2014). Hence, the VR methods should be considered as a new toolbox that should be used in addition to known design methods. The usage of VR will not replace conventional methods in design but will constitute an enhancement to the current portfolio of available design methods.

The key learnings of using VR in design are:

1. VR can enhance the conventional design process by fostering divergent and convergent thinking for problem identification, concept creation, and evaluation.
2. Design is and should remain a human-centred discipline. The usage of VR should support and not compete with this.
3. VR design methods should not replace conventional design methods but enhance them.

As the present approach of using VR in design showed, the technology has an impact on the way designers work but also on fundamental activities such as the creation of products. Based on the current insights, starting from a level of design education, prospective designers need to be taught how to use new technologies such as VR. Furthermore, as the benefits of participatory design in the present dissertation showed, the field of design needs to develop towards a profession that brings people together and let people express themselves without the need of an apprenticeship. It will be the task of design and the designers to let these people express their needs but also their ideas. Sanders and Stappers (2014) foresee that in the 2040ies, not the designers will create products anymore, but people will create relationships, products, services, and infrastructure. These products will be created by applying inter-related networked activities. These trends already became observable in the present design studies that involved participation of users/people. Therefore, it is anticipated that the newly created VR methods have the potential to function as strategic tools for the future of design as a profession.

10 Summary and conclusion

10.1 Summary

Technological advancements such as Industry 4.0 are heading towards automation and digitalization. These trends entail a range of changes most importantly the shortening of product development processes. Especially for the development of new and complex systems this involves challenges: industrial designers need to develop more complex products in a decreased amount of time while still having to fulfil requirements from users and businesses. Especially for complex and new systems, building prototypes for evaluations might be too expensive, take too much time, or not even be feasible. Technology already revolutionized the way industrial designers work. Computer-Aided Design for instance allowed industrial designers to model more efficiently and accurately. Already 20 years ago, design researchers foresaw that the usage of VR could constitute the next paradigm shift in the profession of industrial design. However, the suitability of using VR during the design process for industrial designers remains uncertain. In the current dissertation, it was investigated how VR can be used throughout the design process for a range of activities consisting of the identification of problems, the generation of concepts, prototyping, the evaluation of products, as well as its presentation to an audience.

In chapter 1 Introduction and objectives, a general overview of the problem statement, relevance, research questions and overall aim was given. Additionally, the context of TUMCREATE was explained. Lastly, the work structure of the present was presented.

As a basis for the investigation, an introduction to design including its definition, design processes and design methods was given in chapter 2 Introduction and objectives to establish a basic understanding for the further proceedings of the present dissertation. In this context, design was defined as activity an industrial designer carries out to develop products out of an underlying problem statement, need, or idea that leads to products, systems, services, or experiences that serve user needs as well as needs of stakeholders while considering aspects such as technology, ergonomics, sociology, ecology, psychology, and philosophy. Furthermore, a selection of traditional and modern design methods was presented and described to draw attention on the different existing understandings of design approaches and activities. In this context, additional terms were defined such as stage, activity, strategy, orientation, focus, and approaches. While describing the usage of design methods in general, attention was drawn towards the selection of appropriate methods that is based on a project's setting but also required academic rigor, training, or financial investment. Lastly, the designer's personal preferences constitute a relevant influence on the selection of design methods.

Subsequently, a general overview of VR was given in chapter 3 State of the art – Virtual Reality in design. Based on a summary of other definitions, VR was defined for this dissertation as: “A computer-generated simulation that can be interacted with, consisting of images, videos, and/or sound that represents an environment that the viewer can experience by using electronic equipment”. Additionally, other Extended Realities such as Augmented Reality and Mixed Reality were differentiated from VR and additional relevant terminology was defined including virtual environment, presence, immersion, interactivity, head-mounted display, CAVE, locomotion techniques, and degrees of freedom. Afterwards, a brief summary on the history of VR was presented starting from the introduction of the Sensorama in 1962. To establish a first relevance for design, the application of VR for problem identification, participatory design, prototyping, concept evaluation, and presentation was presented.

In chapter 4 Stance of the thesis, based on a validated methodology a consensus model of the design process was derived from a comparison of 15 validated design processes of other design researchers and practitioners. This consensus model built the basis for the subsequent investigation as it defined the process stages in which VR was intended to be used. The consensus model consists of five stages:

1. **Research and Analysis** (gather information and design briefing)
2. **Conception** (analyse gathered information, synthesis, first conception)
3. **Design** (definition of properties, creation of product variants, first prototyping/evaluation)
4. **Refinement** (functional- and design- models, extensive evaluation, corporate branding)
5. **Finalizing** (documentation, internal- and external- presentations, implementation)

Furthermore, in chapter 4 Stance of the thesis, the transfer of design methods to VR was described. This included justification aspects such as the project stage, pre-defined case studies, research questions, the involvement of participants, study scale, and the kind of data collection.

Based on these aspects as well as employer's requirements, the following design methods were chosen:

- Heuristic evaluation
- Survey
- CAD prototyping
- Usability testing
- Product presentation

Moreover, a preliminary set of evaluation criteria for a final comparative analysis of used design methods was defined based on a literature review in 4 Stance of the thesis. The preliminary set of evaluation criteria consisted of the requirements of safety, validity, time and cost, as well as effort which were defined in detail in the mentioned chapter.

From the preceding state of the art, the introduction to design, and the stance of the thesis, a range of problem statements was derived that later were translated into the following research questions:

- **Research question 1:** Which criteria are needed to evaluate and compare Virtual Reality methods and conventional design studies in a specific application domain?
- **Research question 2:** To which extent can Virtual Reality trigger behaviours with relative or absolute validity compared to experiences in real-life?
- **Research question 3:** What influence does Virtual Reality have on design studies and the design process?
- **Research question 4:** How does the usage of Virtual Reality impact the role of the designer?

Subsequently, the applied methodology in the present dissertation was described in chapter 5 Methodology. It consisted of five steps. Within the first steps, based on expert interviews the preliminary set of evaluation criteria was refined and verified. In the second step, a benchmark study was conducted in which a behavioural observation in VR in the field of pedestrian research was applied in order to verify whether VR constitutes an appropriate tool in the chosen application domain to trigger authentic behaviours. Subsequently, five design studies were conducted. The underlying methodology regarding each case study was threefold. Firstly, the development of the VR apparatus was described including aspects such as the development of the VR environment, simulation, interfaces, locomotion techniques are shared for each study. Secondly, the data collection and test of the method was explained, containing information about the data collection events, participants and their backgrounds, as well as study procedures. Thirdly, a comparative analysis was conducted for each study, in which the newly developed VR design method was compared to two conventional design methods considering the previously defined set of evaluation criteria. Subsequently, based on the conduct of the five design methods, the development of a VR toolbox including an introduction card and five method cards was described.

In chapter 6 Results, the results of the previously defined methodology were presented, starting with the set of evaluation criteria that was refined by conducting interviews with seven experts from industry and academia. Beyond the verification of the preliminary set of criteria, additional criteria were identified, such as variability, interaction, and immersion. Additionally, a criteria weighting was possible. Subsequently, the results of the benchmark study were presented, suggesting that VR for behavioural observations in pedestrian research has the potential to trigger authentic behaviours and thus verifies VR as suitable tool for data collection in this context. However, participants with high prior knowledge in gaming showed less authentic behaviours. Afterwards, each design study was presented in detail, containing information regarding the development of the VR apparatus, the test of the method and data collection, as well as the comparative analysis of the VR methods with two conventional design methods in consideration of the evaluation criteria.

In chapter 7 Answering the research questions, the four research questions were answered. Firstly, with the help of a literature review and expert interviews, a set of evaluation criteria could be derived that allowed the evaluation of design studies both with and without the usage of VR. Secondly, the benchmark study showed that VR is a suitable tool to collect behaviours and reactions in VR. Thirdly, all five design studies showed that the usage of VR impacted every stage of the design process in a way to foster divergent and convergent thinking as valid data can be collected in save and controlled environments (e.g., actual preferences and behaviours). Furthermore, the usage of VR increased the efficiency in terms of time and cost. Lastly, the impact of VR on designers was discussed, indicating that designers will become coordinators and facilitators who enable people to express themselves and to bridge the gap from people towards technology.

Based on the investigation of all case studies, the method card toolbox was derived and presented in chapter 8 Virtual design – A toolbox for designers.

In chapter 9 Discussion, firstly the case studies were discussed with a focus on each underlying research questions. The results of the case studies have shown that minor and severe problems with an existing guidance system could be identified, three main configurations for a public waiting room could be defined, a low-complexity volume could be created with highest model quality, and an information system could be presented in a way that perceived usability and technology acceptance was increased. More importantly, the case study discussion showed the potential of using VR in a range of different use cases for industrial designers. Finally, the impact of VR on industrial design was reflected on the four different levels of technology, participants, designer, and design as a profession.

10.2 Conclusion

In the present dissertation, the impact of VR on industrial design was investigated. To allow this, the differences that occurred by using this technology compared to conventional design studies was assessed in five design studies. As a first step, based on a literature review and expert interviews, criteria were defined that allow an evaluation of design studies independent of the usage of VR. This insight constitutes an addition to the body of knowledge in regard to comparative analyses between different design methods. Even though this offers a basis for further research on evaluating impacts on design, it is important to note that it turned out that the evaluation criteria are highly dependent on the application domain and thus, need to be constantly redefined and cannot be generalized. Secondly, within a benchmark study the suitability of using VR as a data collection tool in the application domain of the five planned design studies was qualitatively and quantitatively proven by observing behaviours and reactions of participants in VR with behaviours and reactions that occur in real-life scenarios (e.g., walking speeds). Based on that, the five design studies were conducted and the impacts of VR on the design process and the involved designers during the development of the data collection as well as the data collection were observed. It became evident that VR fostered divergent and convergent thinking and increased efficiency in terms of time and cost in several design process stages. Hence, with the five conducted design studies the impact of VR on the design process and the roles of the involved designers throughout the project could be shown. The Virtual Design Toolbox that was derived from the usage of the VR design methods within the conducted design studies embodies a tangible outcome for industrial designers to support the usage of this technology.

The present studies also involved a set of limitations mostly of technical nature. As it was pointed out earlier, the technology of VR is not mature yet and thus the built-in displays do not have the capabilities yet to match the resolution and field of view of human eyes. Therefore, participants using VR will currently always experience occlusion which may have an influence on data collection. The technical limitations also include performance issues. The more complex the VR environments, visualizations, and simulations get, the more difficult it becomes to maintain a continuously high framerate. Especially low-range and mid-range HMDs turned out to be problematic in this context. This leads to a further limitation which is the potential of nausea caused by motion sickness or simulator sickness. However, in the conducted design studies involving overall more than 500 participants only one case of simulator sickness was experienced. All design studies were conducted in the application domain of autonomous mobility which presents a further limitation. While in this application field, the design studies and the usage of VR led to successful data collections, this insight cannot be extrapolated to other application domains. Furthermore, no final products were deployed to the market and thus, a direct comparison of market success of products that were developed with the help of VR could not be investigate. Nevertheless, as long as the aforementioned limitations caused by the technology are carefully considered during the development and application of VR design methods, the technology shows great potential and advantages over conventional design methods.

Outlook

As an outlook to the present dissertation, additional tasks and projects are required to further prove the present insights as well as allow a generalization towards other application domains. Firstly, the derivation of evaluation criteria is dependent on the respective case studies. In further research, a library of criteria will be proposed and evaluated to form a framework for designers and researchers. To allow this, additional research in other application domains such as the development of physical and digital products or services will be conducted to gain insights on additional criteria that could become considerable. The usage of new design methods for these research endeavours could foster the derivation of additional evaluation criteria. Based on these insights, a library of evaluation criteria could be defined that already suggest considerable evaluation criteria depending on the study context, study scale, as well as chosen design method. It is anticipated that such a framework can foster the definition of project requirements already in the beginning of a design study but also as an evaluation tool to measure the success of a design study.

Considering the benchmark study, additional research is required to prove the suitability of conducting behavioural research in other application domains. Even though in the present dissertation the suitability of collecting authentic behaviours was proven, it is limited to the application domain of autonomous mobility. Generalization of its suitability needs to be further investigated. This can be achieved by considering research in various additional domains for example health (e.g., test ergonomics), construction (e.g., assemblies), and architecture (e.g., wayfinding). By applying similar methodologies, for instance letting participants experience a big housing complex and conducting behavioural observations, walking speeds and reactions to specific events (e.g., conducting a high step) could be observed and compared to the collected data of the present dissertation. These comparisons allow generalization of findings in terms of authentic behaviours caused in VR.

Overall, five design methods were combined with VR. In further studies, other design methods should be combined with VR to potentially enhance the existing set of VR design methods. Promising design methods for this could be cognitive walkthroughs, A/B testing, laddering, rapid iterative testing and evaluation (RITE), or user journey maps. Another consideration is to implement the technologies of AR and MR into research and the Virtual Design Toolbox more prominently. As the MR presentation showed, AR and MR have great potential to increase the capabilities for industrial designers. One specific research that is planned for proving this is the usage of MR for immersive shared product development in the field of health treatments. By using MR devices, it will be investigated how the methods of parallel prototyping and collaborative CAD development could be realized and how this way of working could influence the design process. In general, as further design methods are identified as suitable for being combined with VR (and in the future MR and AR), the aim is to further enhance the Virtual Design Toolbox and actively conduct design research with XR in order to make these technologies accessible to future designers and enhance the profession of industrial design.

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Appendix A – Transcripts of expert interviews

Transcript – Audi AG am 28.01.2020

- VR wird bei Audi stetig im Produktentwicklungsprozess verwendet, von den frühen Phasen bis hin zur Übergabe an die Produktion
- Es arbeiten verschiedene Abteilungen mit VR → VR ist im Konzerm etabliert
- Dr Rademacher behandelte in seiner Dissertation 21 Kriterien zur Qualitätsevaluation von Produkten mit VR am Fallbeispiel der Automobilindustrie (Rademacher, M. (2014) „Virtual Reality in der Produktentwicklung")
- Im Anwendungsfall „Absicherung der Anmutung und Qualität" wird ein Multi-User Environment mit HMDs (inkl Backpack PC) (inkl. Sitzkiste für Interieur und getrackte Gegenstände z.B. Tisch)
- sowie eine Powerwall zu Evaluationszwecken kombiniert Die Entscheidung VR zu verwenden muss dem Produktentwicklungsprozess (den Anforderungen an die Tätigkeiten innerhalb des PEPs) folgen
- Wichtige Faktoren der Verwendung von VR sind:
  - Immersion (beispielsweise sind Proportionen ohne Immersion schlecht nachvollziehbar). Dies ist jedoch „nur" mit ca 5 Personen möglich
  - Zeit: Da Fräsungen von CAD Modellen 1:1 ca 6 Wochen benötigen und dann beim Review bereits outdated sind, kann mit VR schnell visualisiert, angepasst und evaluiert werden
  - Kosten: VR ist deutlich guenstiger als 1:1 Modelle und ist daher im Arbeitsprozess nicht mehr verzichtbar.
  - Qualität (Kontext: Validität): Die Verwendung von VR (Im Kontext/Arbeitsaufgabe: Bewertung/Absicherung der Anmutung und Qualität) ist nur dann möglich, wenn die Visualisierung das VR-Modell so realistisch wie möglich darstellt, da ansonsten keine Entscheidungen getroffen werden können.
  - Komplexität Entwicklung: „Demokratisierung" von VR: Es soll den Experten (z.B. Designern) zugänglich gemacht werden. Designer nutzen die tools, entwickeln sie jedoch nicht → Jedoch werden die VR Applikationen von computer scientists/informatikern erstellt und nicht von den Designern

  - Komplexität Nutzer: Das Erlebnis muss so authentisch und intuitiv wie möglich gestaltet werden. Nutzer werden durch einen Operator geführt und können dank eines digitalen laser pointers auf Details aufmerksam machen

→ dies reicht nicht aus, um ein authentisches Erleben zu ermöglichen → dies ist ein Grund für den Start der Holodeck Projekts.

- Nach einer Entscheidung in VR wird kein Prototyp mehr gebaut (bezogen auf die Arbeitsaufgabe Absicherung der Anmutung und Qualität im Produktentwicklungsprozess) bevor die Produktion startet. VR wird somit bis zur Abnahme für die Produktion verwendet → Finale Entscheidung wird anhand von VR getroffen und nicht anhand von Modellen/Prototypen
- Dies ist möglich, da die Entscheidungsträger nicht oft gewechselt haben und VR somit kontinuierlich implementiert und validiert wurde → Es konnte Erfahrung gesammelt werden und Vertrauen in das Medium aufgebaut werden.
- Mit VR können Änderungen direkt diskutiert und evaluiert werden ohne, dass Protoypen verändert oder neu angefertigt werden müssen (beispielsweise eine Schulterlinie des Exterieurs, welche um 0,1mm verschoben wurde) → Mehr Möglichkeiten/Variabilität (z.B. können Modellvarianten evaluiert werden (A/B Testing))
- Zeit, Kosten und die Qualität der Applikation (Kontext: Validität der Visualisierungen) sind die wichtigsten Kriterien (für was?)
- Statement: Solange physische Produkte verkauft werden, wird man nicht komplett auf Modelle verzichten können. „Man sieht wenn ein Produkt nur im CAD entwickelt wurde“ (Anonym)
- AR wird überwiegend für Training und Auditieren der Qualität von Produkten verwendet
- (Thema Kriterien: Siehe Qualitätskriterien der Dissertation von Dr. Rademacher)

Transcript – ETH Zurich 05.02.2020

- Mr Zhao uses VR in combination with simulations (e.g., people flow at the love parade) and scenarios such as decision making and navigation
- Physiological sensors are being used for data collection (GSR, Heartrate)
- VR is used for case studies because:
    - VR can simulate any scenario
    - VR is highly visual: Participants normally use language to express themselves, VR and biomedical devices open a new layer → VR breaks the barrier between scientists and participants
    - VR enables the immersion of participants into scenarios such as fire emergency situations while still maintain safety for participants
    - VR is time-saving (time and costs go hand in hand)
- Ideally, experiments should be conducted in the real world since VR brings noise and additional variables into the experiment due to aspects such as technical limitations (e.g., resolution, FoV). However, VR opens possibility that could hardly/not be investigated in real conditions
- Mr Zhao creates the VR experiences and simulations in Unity in an iterative process (no additional complexity for developers present)
- Joystick or mouse/keyboard inputs work well as input devices (prove Tyler Thrash → Evaluation of Control Interfaces for Desktop Virtual Environments)
- Additional steps such as questionnaires after the experiment are conducted outside VR (complexity due to inputs)
- Resolution and FoV has to be further improved to expand the possible usage and make research less "noisy"

Transcript – ImmoPresenter 3D 12.02.2020

- ImmoPresenter 3D bietet immersive VR Erlebnisse, mit Hilfe welcher potenzielle Kunden Immobilien besichtigen können
- Die VR Erfahrung könnte sowohl bei Wohnungssuchenden (beispielsweise integriert in eine Immobilienplatform) stattfinden als auch bei Immobilienagenturen vor Ort
- VR bietet hierbei eine immanente Besonderheit:
    - Durch die Immersion/Präsenz wird ein Erlebnis erzeugt, welches das Gefühl vermittelt, sich am Ort der Simulation zu befinden
- Durch VR ergibt sich eine Effizienzsteigerung im Kontext von Immobilien:
    - Kunden (Wohnungssuchende) müssen keine Vorortbesuche wahrnehmen
    - Reisekosten und Zeit werden sowohl für Wohnungssuchende als auch Immobilienmakler eingespart
- Durch VR könnte die Entscheidungsfindung automatisiert werden, da Wohnungssuchende auswählen können, welche Wohnung sie favorisieren, ohne dass Termine mit Immobilienmaklern vereinbart werden müssen
- VR ist die „Enablertechnology“ für dieses Konzept
- Es muss jedoch darauf geachtet werden, dass die Diskrepanz zwischen der Simulation und der Immobilie klein gehalten wird (Validität der Visualisierung)
- 360° Bilder/Videos/Arrays sind einfacher zu erstellen als CAD Dateien und verringern die Komplexität der Entwicklung. Zudem erlauben sie (derzeit) keine Retusche welche die Visualisierungen verfälschen würde – Blende4
- Eine intuitive Interaktion (UI+UX) steht im Zentrum der Entwicklung da nur so Userakzeptanz sichergestellt werden können
- Nutzer können somit nicht wirklich geschult werden, dieses System zu benutzen, deshalb muss die Interaktion nahtlos funktionieren
- Da die Interaktion so einfach wie möglich sein muss (geringe Komplexität für Nutzer) ergibt sich eine erhöhte Komplexität für die Entwickler
- Der bestehende Prozess für Kunden kann komplett verändert werden:
    - Der Tagesablauf ändert sich
    - Die Entscheidungsfindung für Kunden kann beschleunigt oder vll sogar automatisiert werden
    - Der Immobilienvertrieb verändert sich grundsätzlich
- Es können neue Applikationsfelder erschlossen werden (z.B. Reisebüros)
- Das Berufsfeld kann sich ändern:
    - Neue Ausbaustufe der Digitalisierung → Automatisierung
    - Der Beruf des Immobilienmakler könnte somit theoretisch eliminiert werden

- Durch die Effizienzsteigerung (Zeit und Kosten) kann die Applikation Immobilienbüros/portalen aufgezwungen werden
- Zusätzliche Gebühren könnten für eine Vorortbesichtigung verlangt werden
- Bestandsmieter werden entlastet
- Co2 foodprint wird reduziert (Statement: VR kann die Welt retten)

Transcript - BMW

- BMW verwendet VR unter anderem um das Fahrzeug erlebbar zu machen und um Interieur sowie Exterieur zu evaluieren (Design Review)
- BMW hat VR bereits in einer Reihe von Feldern integriert (z.B. Usability, Design, Raumwirkung)
- Hierbei werden beispielsweise HMDs (z.B. HTC Vive) verwendet, da sie für gute Immersion sorgen. Zusätzlich wird leap motion verwendet um die Hände im Interior zu visualisieren, da dies ein zusätzlicher Aspekt für die Immersion der Nutzer ist.
- Für Interiorvisualisierungen werden auch Sitzkisten verwendet um haptisches Feedback zu ermöglichen (im Normalfall werden für die Entwicklung neuer Fahrzeuge individuelle Sitzkisten mittels additiver Herstellung gefertigt)
- Obwohl sich die Nutzer innerhalb einer Sitzkiste befinden, ist es wichtig, ein VR Setting mit sechs Freiheitsgraden zu verwenden, da nur so Bewegungen des Kopfes/Oberkörpers akkurat abgebildet werden können (der Nutzer braucht volle Freiheit)
- VR hat folgende Auswirkungen auf den Designprozess und den Designtechnikprozess (welche gemeinsam zur industriellen Implementierung führen):
    - Effizienzsteigerung (Kosten und Zeit), da Prototypen zu einem gewissen Teil ersetzt werden können (mittlerweile im Normalfall ein bis zwei 1:1 Prototyp anstatt drei). Modelle werden ersten in den „reiferen“ Phasen der Entwicklung angefertigt. Der Modellbau eines 1:1 Prototypen dauert ca 6 Wochen. Zudem ist das Design in VR aktueller (kein „freeze“ für 6 Wochen). Kosten und Zeit hängen hierbei direkt zusammen.
    - VR bietet eine höhere Varianz beziehungsweise mehr Möglichkeiten (z.B. Farb-, Material- oder Oberflächenvarianten können schneller visualisiert und evaluiert werden)
- VR muss für Reviewer/Nutzer so einfach wie möglich sein (es muss möglich sein, dass sich der Reviewer in VR „normal“ verhalten kann und nicht vorab eingewiesen werden muss)
  → Niedrige Komplexität für Nutzer
- Bishher haben die Reviewer in VR nicht interagiert, dies wurde von einem Operator ausserhalb von VR übernommen (komplexe Interaktion inkl. Einarbeitung würde zu verringerter Nutzerakzeptanz führen)
- Im Normalfall haben sich 1-2 Personen in VR befunden (HMD), und 5-10 Leute verfolgten den Review per Bildschirm (nicht jeder ist bereit, sich eine VR Brille aufzusetzen)

- Für Diskussionen im Review sind Bildschirme ausreichend
- Die Entwicklung steht momentan an der Schwelle eine aktive Interaktion der VR Nutzer mit dem System zu integrieren
- Avatare in VR in multi-user Erlebnissen sind nicht wirklich störend → Nutzer stellen sich darauf ein (Nutzer fokussieren sich mehr auf das Nutzererlebnis als auf die Avatare)
- Es muss sichergestellt werden, dass die Dimensionen und Proportionen in VR dem der Sitzkiste und des Modells entsprechen (→ z.B. Zierleisten in VR schienen zu kurz zu sein) Dies ist eine Voraussetzung für die Nutzbarkeit von VR → Validität der Visualisierung
- Der Pupillenabstand muss bei jedem Nutzer eingestellt werden, da dies sonst die Visualisierung verfälschen kann
- VR bietet die Möglichkeit, nicht nur Aspekte des Interiors oder Exteriors zu evaluieren, sondern den kompletten Nutzererlebnisprozess zu betrachten. Somit können über physische Produkte auch Erlebnisse gestaltet werden. Dies ist nur mit Hilfe von VR möglich (nicht mit Modellen und/oder PowerPoint). Die Entscheidungsfinder können somit das Nutzererlebnis von A bis Z durchgehen → VR hat eine enorme Integrationsfähigkeit. Mögliches Beispiel von App-Steuerung der Sitzheitzung bis zur vollendeten Reise.
- Stichwort: „Erlebnisgestaltung“

Transcript - flyingshapes

- Flyingshapes ist ein tech-getriebenes startup (VR)
- Gegründet 2016
- Finanziert von Business Angel
- Der Fokus liegt auf der Designphase (zweite bis dritte Phase) und speziell dem Industriedesigner (z.B. Transportationd Design) aber nicht auf der Generierung von Class-A surfaces sondern sketching/Formfindung und Kreation von Volumina fuer Designiterationen/entscheidungen
- Der Prozess von Sketches bis hin zu Volumenmodellen wird betrachtet (aber noch vor dem Aufbau z.B. in CATIA)
- Eine Kooperation mit Logitech betsteht (Hardware: Logitech VR Ink)
- Somit kann der Nutzer in drei Dimensionen zeichnen
- Es besteht ein Kommunikationsproblem zwischen Designer und Modelleur (Kontext: Automotive)
- OEMs sind nicht an dem Punkt, auf 1:1 Modelle zu verzichten, besonders nicht vor Produktionsanlauf (→ Ist wohl eher eine Imagedartellung)
- VR isoliert: Statement: „Wir müssem das Asoziale von VR beheben“
- Der Impact von VR auf den Designprozess:
    - Mehr Variation/Möglichkeiten bei den Entwürfen
    - Schnelleres Einsteigen in digitale Medien (es wird direkt in VR gesketched)
    - Verringerte Komplexität bei der Erstellung von 3D Daten für Designer mit geringer/ohne CAD Erfahrung
    - Verbesserte Kommunikation von Designern zu Modelleuren
        - Beide Parteien können live miteinander arbeiten
        - Intuitive Interaktion mit dem Medium
    - Effizienzsteigerung durch schnellere und erhöhte Designiterationen und Konzeptmodellierung
    - Die Qualität der Entwürfe wird gesteigert. Dies bedeutet:
        - Es können viele Emotionen in den Entwurf fließen
        - Die Verständlichkeit des Entwurfs wird erhöht
- Besonders für Designer über 40 Jahre besteht Angst vor der Technology (VR). Diese Kunden können nur mit intuitiver Interaktion überzeugt werden
- VR sollte in die Ausbildung der Designer integriert werden. Nicht bis zu einem Punkt, dass Designer Softwareentwickler werden müssen aber um ein Verständnis der Möglichkeiten (Software, Hardware, Methodik) zu vermitteln
- Zusammenfassung des VR trials:
    - Ein HTC controller + Logitech Ink + HTC Vive Pro (6 DoF) + Chri Sti

- Unterschiedliche Interaktion der beiden Input devices
- 3D Sketching
- „Aufziehen" von Flächen zwischen den beiden Input Devices
- Modifikation von Pivots/Flächen → History
- Neue Anwendung:
  - Sitzend am Tisch
  - Zeichenfläche wird per Logitech Ink auf der Tischoberfläche definiert
  - 2D Zeichnen wird auf eine Ebene im Raum projiziert
- Gegen Sickness der Zuschauer ausserhalb von VR:
  - „Stabilisierung" des Camera Views
  - Keine Rotation um die X-Achse
- God-Mode als Betrachter möglich

- Ich möchte zu dem Transkript eine Sache anmerken/betonen: für die Designer die wir ansprechen ist 3D Modellierung assoziiert mit einer komplexen, eher mathematischen Arbeit in unästhetischen tools wie Alias. VR bietet hier ein riesen Potential nicht nur den Ü40 Designern ein intuitives Werkzeug zu bieten, dass die komplexität aus dem Thema 3D-Modellierung nimmt: die direkte Interaktion mit dem 3D-Medium lässt die Abstraktionsebene "2D-Projektion auf dem Bildschirm zu 3D-Daten" komplett verschwinden.
- Zudem ist die flyingshapes GmbH erst Mitte 2018 gegründet worden. Das Projekt begann allerdings schon im Dezember 2016

Transcript – Present4D

- Present4D setzt VR im Businesskontext ein mit Workspace VR (6 Degrees of Freedom) und der VR Suite (3 und/oder 6 Degrees of Freedom)
- 360° Medien wie Bilder, Videos und Arrays werden in VR erlebbar gemacht (beispielsweise eine virtuelle Tour durch eine Ölplatform)
- So können von Medien 8K 360° Panoramafotos erstellt werden
- Dies dient zu Planungs- Marketing- oder Design Review- Zwecken
- (Die Gründer arbeiten gerade auch an einem VR conference tool (remote mit Avataren))
- Die Applikation kann angewandt werden für:
    - Training (Education)
    - Marketing
    - Planung
    - Brand strategy
    - Safety
    - Prozessvisualisierung
    - Konstruktionsdokumentation
- Unique selling points:
    - Direkter Übertrag von CAD Medien in VR (dies ist noch ein manueller Prozess, soll aber automatisiert werden)
    - Intuitives Handling (keine Vorkenntnisse nötig) → Geringe Komplexität für Nutzer
→ Einfachheit
    - Direktes Feedback für Designer da das Ergebnis direkt und immersiv visualisiert werden kann
- Nutzergruppen können sämtliche Industrien umfassen und betreffen beispielsweise Aspekte wie Industriedokumentation (visueller Baufortschritt)
- Vorteile der Applikation sind:
    - Frühe Erkennung von Fehlplanung → Kosteneinsparung → Effizienzsteigerung
    - Einsparung von Reisekosten (man muss nicht auf die Platform)
    - Paralleles Arbeiten / Kombiniertes Arbeiten
    - Sicherheit für Nutzer (Vermeidung von Unfällen)
    - Hohe Variabilität durch das digitale Medium
    - Realitätsnahe Visualisierung
    - Remote Arbeiten

    - Digitale Präsenz der Medien (beispielsweise spontan zu einem Termin mitnehmen)
- Die Interaktion mit dem System ist jedoch wichtiger als die realistische Darstellung der Medien (Die Gründer sehen hier einen großen Unterschied von beispielsweise Anlagenbau zur Automobilindustrie) → Stichwort: Ergonomie
- Die Interaktion der Nutzer mit dem System muss so einfach wie möglich und intuitiv sein (besonders für die Navigation). Dies kann beispielsweise durch Teleportationspunkte inkl. Gaze selection realisiert werden
- Customlogic: Das tool erlaubt es, eine Geschichte zu erzählen und den Kunden trotz Interaktivität der 360° Medien einen „roten Faden" während des Erlebnisses zu bieten
  Stichwort: Interaktive Filme (z.B. Bandersnatch)
- Statement (Markus): VR ist die Digitalisierung der Wahrnehmung
- Momentan beschränkt sich VR hauptsächlich auf visuelle auditive Medien. Haptische Medien und Geruch werden hinzukommen
- VR ist momentan eine Enablertechnologie: In X Jahren wird es vll nicht mehr die Brille sein, sondern eine Kontaktlinse oder der Content wird direkt in den Sehnerv eingespeist
- Statement (Thomas): VR sorgt für Excitement! (Nicht nur für den Kunden sondern auch für das Unternehmen, das VR verwendet, beispielsweise im Marketing)
- Potenziellen Kunden muss die Angst vor VR genommen werden
- Das Geschäftsmodell von Present4D erlaubt es, Kundenwünschen entgegenzukommen und zusätzliche Funktionalität der Applikation auf Kundenbedürfnisse abzustimmen
- Diskussion: Kann übermäßiger VR Konsum zu Realitätsverlust führen?

Transcript – Breda University of Applied Sciences

- Die Verwendung von VR in den frühen Phasen des Designprozesses
- VR hilft, ein Problem oder eine Opportunity zu verstehen
- Es unterstützt die Klarstellung: Was ist eigentlich das zugrundeliegende Problem und warum entsteht dieses Problem → Designprozess: Problem Identification
- VR hilft den Nutzern, den Kontext besser zu verstehen (durch die immersiven Erlebnisse)
- VR ermöglicht frühe Prototypen digital zu definieren und die Phase der Problem Identification iterative anhand der Prototypen zu durchlaufen (z.B. behebt dieser Prototyp das eigentliche Problem? Verändert sich das Problem?) → z.B. A/B Testing
- VR ermöglicht eine schnelle Validierung im Designprozess (qualitativ und quantitativ) → Effizienzsteigerung
- Im Vergleich zu konventionellen Designmethoden bietet die Nutzung von VR in diesem Kontext „sense of presence“ und den Kontext des Umfeldes (der Nutzer kann die Situation und das Umfeld durchleben) → Vergleich preference vs behaviour (Nutzer beschreiben, wie sie sich in Situationen verhalten würden, verhalten sich aber eigentlich ganz anders)
- Die Zuhilfenahme von physiologischen Sensoren (GSR und Heartrate) erlaubt die Erhebung von quantifizierbaren Daten (körperliches Verhalten)
- Ein Ziel von VR: Total immersion (haptic, smell)
- Die Interaktion des Nutzers mit dem System is wichtig für die Immersion (i.e., realistisches feedback, da dies das Verhalten beeinflusst)
- VR ist in der Lage, emotionale Erlebnisse zu ermöglichen und Erfahrungen zu verstehen → die Forscher verstehen den Nutzer besser
- Das digitale Soziale wird durch VR wieder ehrlicher, da das Verhalten der Menschen sichtbar gemacht wird. Frage: Wie wird die Identität von VR Nutzern aussehen?
- VR veranlasst Empathie
- VR löst einen Effekt bei Nutzern aus (der unter anderem zu wellbeing (positiv) oder Angst (negativ) führen kann) → VR ist der Schlüssel um die Welt zu gestalten
- Der Einfluss von VR auf Kosten und Zeit:
    - Rapid prototyping wird durch VR unterstützt (klarer Vorteil für Bereiche wie Design und Architektur)
    - Es benötigt zwar mehr Zeit, Prototypen in VR zu gestalten als mit beispielsweise CAD, da die Umgebung mit gestaltet werden muss aber holistisch gesehen kann durch die schnellen Iterationen und die

Betrachtung des Nutzungskontextes Zeit gespart werden (Statement: Die Zeitersparnis ist jedoch nicht das interessante an VR sondern das, was es beim Nutzer auslöst)

- Der Grad des Realismus in VR ist schwer zu begreifen. Oftmals reichen abstrahierte Szenarien aus um den Nutzer zu verstehen → Kontextabhängig
- Die Validität der zugrundeliegenden Methodik ist sehr wichtig:
    - Wenn man den Nutzer mit VR nicht beeinflussen kann, dann macht es keinen Sinn, die Technologie zu verwenden
- Nutzerinteraktion:
    - Input devices können gut sein, können jedoch problematisch werden, wenn sich dadurch die Interaktion unnatürlich anfühlt. Sie müssen gut in die Interaktion integriert werden
- Sicherheit:
    - VR ermöglicht es, Extremszenarien durchzuspielen wie beispielweise Road safety, Training simulators, Kriminalität
    - Nutzer können trainieren, wie sie sich in Extremsituationen verhalten (z.B. nicht starr werden, wenn man überfallen wird) Man muss aufpassen, dass man die Nutzer mit solchen Szenarien allerdings nicht mehr verschreckt (beispielsweise durch Realness)
- VR kann Leuten helfen, Phobien zu überwinden (z.B. Public speaking)
- Wie werden sich Designer durch VR verändern?
    - Designer werden in der Lage sein, mehr als „nur“ den kreativen Aspekt von Design zu verstehen. Aspekte wie Psychologie, Verhaltensforschung und Physiologie werden relevanter und zugänglicher für Designer → Designer werden in der Lage sein, Verhalten zu designen
    - Designer müssen in der Lage sein, VR zu gestalten → Es wird wichtig, VR Umgebungen bis zu einem gewissen Grad zu erstellen
- Wie kann VR den Designprozess beeinflussen?
    - Die Ideationphase kann durch rapid prototyping noch iterativer gestaltet werden. A/B Testing kann verwendet werden um Ideen zu generieren
    - VR ist interessant für die Evaluation von Design
    - VR kann eine neue Ebene öffnen um nicht nur Produkte zu gestalten, sondern zu behavioural and attitudinal change zu führen → Veränderung der Person, mehr Nachhaltigkeit
    - Statement: VR is a medium to bring change
    - VR ermöglicht “longitudinal tests”: Sieht die Evaluierung heute anders aus als in 2 Jahren? Basierend auf dem, was du vor 2 Jahren getan hast. . .

- Sense of presence ist besser in CAVE systemen während sense of escaping besser in HMD systemen ist
- VR hilft bei der Kommunikation verschiedener stakeholdern da diese Dinge oft unterschiedlich interpretieren und es zu Missverständnissen kommen kann → Modelle/Situationen können dank XR besser dargestellt werden um zu einer gleichen Wellenlänge zu kommen
- „VR for communicating motivations and insights“ (Diese Denkweise kann auch auf den Ideation Prozess angewandt werden) Wichtig: Denkweise/Motivation/Probleme der Nutzer müssen richtig verstanden und interpretiert werden!
- Wie können Menschen ihre Probleme in VR selbst darstellen? (e.g., Tilt Brush?) Dies könnte zu viel mehr Informationen führen als eine einfache verbale Beschreibung von Nutzern

Appendix B – Comparative analysis of immersive heuristic evaluation

Quantitative results – a comparison

Table 24 shows a summary of usability flaws, clustered by the adapted set of heuristics as well as the total amount of discovered usability flaws of all nine DGS concepts.

Table 24. Identified usability flaws by using immersive heuristic evaluation

Heuristic	**DGS Concepts**																		**Total per concept**	
	1		2		3		4		5		6		7		8		9			
	M	S	M	S	M	S	M	S	M	S	M	S	M	S	M	S	M	S	M	S
Continuity of information		1		1		1				1		1					1		1	5
Consistency of information	1						1		1		1								4	0
Visibility of information	1	1			1					1	1	1	1		1	1			5	4
Comprehensibility of information	3	2											1		1				5	2
Intuitive and clear interface		1	1										1		1				3	1
Adequate information	1	1	1		1				1			1	1			1			5	3
Accessibility for vulnerable users	1				1		1		1		1				1			1	6	1
Provision of feedback	1		1		1		1		1		1		1		1		1		9	0
Prevention of errors	1		1	1	1	1	1	1	1	1	1		1		1		1		8	3
Total number of flaws	**9**	**6**	**4**	**1**	**5**	**2**	**4**	**1**	**5**	**3**	**5**	**3**	**6**	**0**	**6**	**2**	**3**	**1**	**46**	**19**

19 of the 65 usability flaws were determined as severe whereas 46 usability flaws were determined as minor.

Table 25 shows a summary of usability flaws, clustered by the adapted set of heuristics as well as the total amount of discovered usability flaws of all nine DGS concepts.
Table 25 shows that overall 65 usability flaws were discovered among the nine concepts.

Table 25. Identified usability flaws by using desktop-based heuristic evaluation

Heuristic	**DGS Concepts**																		**Total per concept**	
	1		2		3		4		5		6		7		8		9			
	M	S	M	S	M	S	M	S	M	S	M	S	M	S	M	S	M	S	M	S
Continuity of information	1	1		1	1		1									1			3	3
Consistency of information	1			1									1				1		3	1
Visibility of information	1		1	2		1			1			1				1			3	5
Comprehensibility of information		1							1		1						1		3	1
Intuitive and clear interface	1		1				1		1										4	0
Adequate information					1							1				1			1	2
Accessibility for vulnerable users							1						1					1	2	1
Provision of feedback	1				1			1			1		1				1		5	1
Prevention of errors			1		1			1		1					1				3	2
Total number of flaws	**5**	**2**	**3**	**4**	**4**	**1**	**3**	**2**	**3**	**1**	**2**	**2**	**3**	**0**	**1**	**3**	**3**	**1**	**27**	**16**

Qualitative results – Expert statements regarding the usage of VR for heuristic evaluation

After finishing the tests, the experts mentioned the following advantages of using VR for heuristic evaluation:

- VR allows for a very realistic and immersive experience
- VR makes a big difference to the workshops due to its fidelity of spatial awareness and scale
- Without VR, the experts would need more time to understand the case study and to experience all concepts
- With VR, scenarios can be redone, concepts can be re-watched, and the user can just go back and take as long as required
- The evaluation is conducted under laboratorial conditions
- VR allows a quick immersion into the environment without the need for on-site visits
- VR is a good tool to experience environments and concepts
- A key advantage is the usage of the “elderly mode”, which is exclusive to VR. People can experience an approximation of how it would feel to be an elderly user (e.g., with visual occlusion and reduced walking speed). VR offers the only way to experience that
- Users can jump from one application field to another without leaving the room

- The range of locomotion techniques is very advantageous; with the teleportation locomotion, the environment can be investigated very quickly, whereas with the physical walking method and arm swing method, the effort, distance, and time can be experienced very realistically
- The VR devices, including its input devices and the VR interface, are easy to use

Furthermore, the experts mentioned the following limitations and drawbacks:

- Participants with little VR experience should not stay too long in VR to minimize the risk of nausea
- The expert who takes notes can get nauseous by watching the video footage of the first-person view (due to an unsteady field of view in VR)
- The movement sensitivity with the touchpad locomotion technique is too high and therefore, using the touchpad for moving was not as realistic as the other locomotion techniques
- When the crowd level is set to “high”, the performance (i.e., framerate) decreases, which could lead to nausea

Derived design guidelines based on the quantitative and qualitative results

Based on the expert statements and observations during the immersive heuristic evaluation, we recommend the following guidelines for developing and using an application that allows heuristic evaluation in VR:

- Ensure the availability of researchers with good knowledge about the hardware, software and study context since participants might need assistance
- Take precautions to comfort participants in case of motion sickness
- Ensure a controlled environment without disturbance for the data collection
- Include a wide range of concepts: Since VR allows the evaluation of different concepts and variants, its full potential should be used to identify the most usable concepts and variants
- Include a range of conditions and specific tasks: Since VR allow to change the environments and conditions very quickly and easily, the concepts and variants should be tested in different conditions to increase the evaluation potential
- Prioritize content interactivity over visual representation: For participants, an accurate way of interacting with the system is more important than its visual representation for evaluating concepts
- Avoid the implementation of concepts or scenarios that might be influenced by technical limitations of VR: Specific concepts or scenarios that would reveal technical limitations of VR, such as insufficient resolution or field of view that could distort the results for the concepts, should be avoided

Appendix C – User interfaces of VR prototyping tools and tool comparison

Figure 61 shows interfaces of all three commercial VR applications that were part of the investigation.

Figure 61. Interfaces of commercial applications (left: Google Blocks; middle: Microsoft Maquette; right: Mindesk)

Table 26. Comparison of tools of commercial applications summarizes the analysis of the commercial VR applications regarding their functionality.

Table 26. Comparison of tools of commercial applications

Application/Function	**Blocks**	**Maquette**	**Mindesk**
Primitive	Cone, Cube, Cylinder, Sphere, Torus	Box, Cone, Cylinder, Sphere	Box, Cone, Cylinder, Sphere, +40 shapes
Transform	Select, Scale, Copy, Group, Erase, Change colour	Scale, Copy, Move, Rotate, Erase, Change colour	Scale, Move, Rotate, Erase, Group
Navigation	Grip buttons	Grip buttons	Grip buttons, teleport