Chapter 1

# Embracing virtual reality

## Empowering professionals in the design process

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### 1.1 INTRODUCTION

Design processes help professionals to have standardized approaches to changing projects and circumstances and thus, have proved their value over time. As technologies evolve, new utilizations arise that enhance and change the way professionals design products[1] and apply the design process. Computer-aided design (CAD), for instance, revolutionized prototyping activities in product development as it improved and accelerated modeling capabilities, allowed design changes in an efficient manner, and increased accuracy (and thus, decreased tolerances in production) which eventually led to products with better quality. CAD further impacted the design process as it increased the efficiency of designing products in terms of time and money spent as well as increased flexibility and improved data management (Akca, 2017; Cross, 2006; Stadler et al., 2020c). In recent years, virtual reality (VR) has become increasingly prominent for product development and design-related professions as well. Cross (2006) already foresaw more than twenty years ago that VR has the potential to enhance traditional design methods such as sketching and drawing.

In this chapter, virtual reality is defined 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. Even though the main application domain for VR is still the entertainment industry, the technology is already used in professional fields such as engineering, training, marketing, exposure therapy, and ergonomics (Krauß et al., 2022). Moreover, VR has already been applied in product development and design fields. First insights indicate that VR has the potential to further disrupt and enhance the design process for professionals. Nevertheless, since VR is still considered a niche product, its impacts on the design process remain to be investigated.

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### 1.1.1 Aim and contribution

In the present investigation, the overall aim is to elaborate and discuss the potential impacts that the technology of virtual reality can have on the design process, mainly from the perspective of engineering and design. To allow a holistic assessment, the impacts of VR will be discussed on the levels of professionals and other stakeholders, users, technology, and design as a profession. As a tangible outcome for fostering further research and active usage of VR during the design process, a set of general major guidelines for using VR in the design process for professionals is proposed and human-centered approaches to facilitate the acceptability and acceptance of VR will be developed.

## 1.2 DESIGN PROCESSES

In order to define design processes, an attempt is made toward a definition of the term "design" as its application fields, goals, and objectives are not uniformly defined but undergo permanent changes (based on Hauffe, 2008). In this chapter, design is defined as the activities designers carry out to develop products out of underlying problems, needs, or ideas resulting in the fulfillment of user needs as well as the needs of all stakeholders. To achieve this, the designers need to consider influences such as ergonomics, technology, sociology, psychology, ecology, philosophy, ecology, and finance (based on Frenkler, 2020). Consequently, the term "design process" can be defined as the stages, approaches, techniques, and activities that designers undergo to design products (British Design Council, 2020). In this context, Cross (2008) states that manufacturing cannot commence before the design is done. Thus, the goal of the design process is to describe the way of designing and to finally give a clear description of the artifact. Similar to the term "design", there is no unique definition of the design process, but various attempts were made to visualize it, for instance by describing the chronological sequence of activities that were carried out while designing a product (i.e., descriptive models). Alternative process models tried to prescribe patterns of activities (i.e., prescriptive models) (Cross, 2008). Comparative analyses of design processes already were published in the field of industrial design, mechanical engineering, and further transdisciplinary professions, concluding that design processes generally describe or prescribe activities that should be considered while designing. These activities include research and problem identification, ideation, prototyping, evaluation, and presentation (Gericke and Blessing, 2012; Pahl et al., 2007; Wynn and Clarkson, 2005).

To allow an assessment of potential impacts that VR can have on the design process, a representative design process model was chosen. Since the "Double Diamond" introduced by the British Design Council (2020) embodies the majority of activities that professionals undergo while designing products, this design process was selected as a representative model for this chapter. Figure 1.1 shows a visualization of the Double Diamond.

The Double Diamond visualizes a stage-based strategy consisting of the following four iterative stages: *discover*, *define*, *develop*, and *deliver*. The name and the shape of this design process is derived by the visualization of convergent and divergent thinking throughout the process that results in two diamond-like shapes that touch each other at the point of the design brief. While the first two stages aim to define the right problem by applying divergent and convergent thinking, the same approach is applied in the third and fourth stage to derive the right solution. Similar to the design thinking process, the Double Diamond is divided into a problem space (the first diamond) and a solution space (second diamond). Each stage of the Double Diamond involves its own objective (British Design Council, 2020):

- **Discover**: start the process by questioning the challenge(s) and understanding the users and other stakeholders, eventually leading to the identification of user needs;
- **Define**: understand findings as well as how the problem(s) and user needs are aligned, resulting in a design brief that clearly defines the challenge(s) based on the gathered insights (i.e., design synthesis);
- **Develop**: develop, test, and refine multiple potential solutions;
- **Deliver**: select a single solution and prepare it for launch.

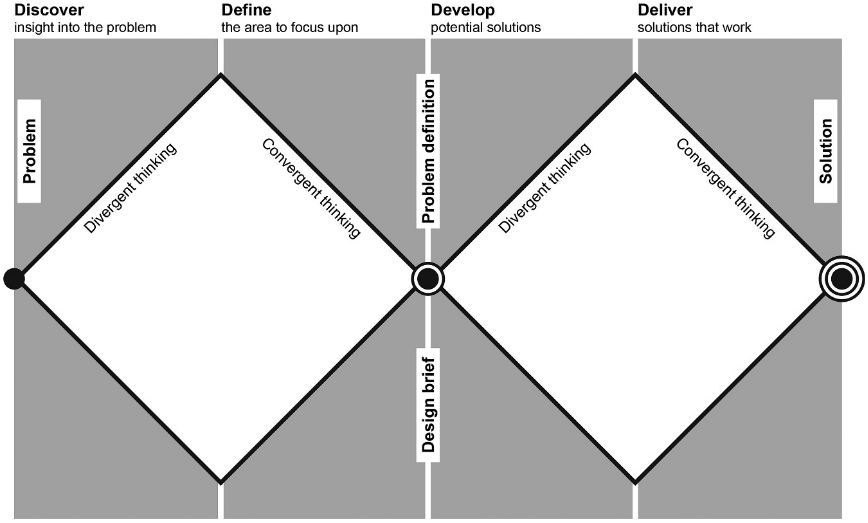


*Figure 1.1* Double Diamond design process. (Based on British Design Council, 2020.)

While applying the design process, a range of different design principles are suggested including a human-centered approach for allowing the involved designers to understand the people they are designing for as well as a visual and inclusive communication to help people to understand the problem and ideas. Furthermore, collaborative and co-creative activities should be considered and iterations especially during the development should strongly be focused (British Design Council, 2020).

## 1.3 USING VR IN THE DESIGN PROCESS

In the following four paragraphs, a non-exhaustive selection of representative usages of VR during the design process is presented in order to demonstrate potential utilizations of VR for design activities.

### 1.3.1 Discover

In the first stage of the design process, VR has already been applied to allow designers to create empathy, for instance for users and further stakeholders. The technology has great capabilities to allow users to have the illusion of ownership of their virtual representation (i.e., avatar) (Kilteni, 2013). Schutte and Stilinović (2017) investigated whether VR experiences can lead to greater empathy than experiences that are visualized as two-dimensional formats. The results indicate that VR has the potential to lead to greater engagement and interpersonal emotions such as empathy. This implies that VR could allow designers to step into the shoes of those people they are designing for as well as experience environments through their eyes. Beyond the creation of empathy, the usage of VR allows experiences in a wide range of conditions and scenarios, for instance involving cultural differences and physical limitations (based on Coburn et al., 2017). Moreover, scenarios could be visualized that might not be practical or even feasible in real-life conditions. In summary, the usage of VR during this stage of the design process has the potential to foster empathy and greater engagement, indicating an improved divergent thinking for understanding the users as well as the application field of the desired product. Figure 1.2 shows users experiencing an immersive VR application that is meant to create empathy in the context of public waiting spaces (Stadler et al., 2020a).

### 1.3.2 Define

The technology of VR has already been used for activities such as creative three-dimensional sketching, brainstorming, and designing mood boards, as well as conducting participatory design workshops. Fromm et al. (2020) conducted a qualitative study consisting of VR brainstorming sessions to examine the effects of the immersive technology on negative group effects.


*Figure 1.2* VR experience to create empathy with people at public waiting spaces in terms of room configurations, crowd, interior, and lighting.

The results show the benefits in terms of increased focus on the task as well as providing a relaxing digital environment in which ideas could be freely expressed, which had a positive impact on idea generation. Rieuf and Bouchard (2017) developed a tool for designers for creative drawing and developing mood boards in VR, two essential activities during the *define* phase of the design process. The researchers' findings imply that VR can enhance the emotional component of design activities and can lead to increased engagement of the involved designers. This includes the benefits associated with VR, such as experiencing 3D models and sketches in realistic scales and the ability to experience concepts from different and enhanced perspectives, as well as intuitive and natural interaction with digital content. These findings confirm the conclusions of Keeley (2018), who studied sketching activities in VR. The researcher inferred that VR allows for a greater sense of scales and perspectives.

During the design process and especially in the *define* stage, participatory design approaches are frequently used for defining the design synthesis and also in creative ideation and concept generation. In participatory design activities, designers increasingly cocreate with users, which brings benefits such as a deeper understanding of user needs, greater efficiency in designing products, and the creation of synergies between users and designers (Prahalad and Ramaswamy, 2004). In a co-creative design study, researchers found that the use of VR increased people's motivation to participate and fostered overall engagement. In addition, VR was beneficial in terms of visualizability of design concepts and increased efficiency in terms of time and cost compared to traditional methods. Moreover, the use of VR shifted the role of the involved designers from being creators toward being coordinators and facilitators who helped people express themselves and their needs (Stadler et al., 2020a). In this context, Bruno and Muzzupappa (2010) propose a participatory design approach for evaluating the usability of home appliances that allows users to virtually interact with products. The researchers conclude that VR is "[…] the best tool to satisfy the needs of a participatory design approach […]" and that the use of VR allows designers to create products with improved usability. In summary, the present research overview shows that VR has the potential to foster not only creative thinking, and also participatory design approaches that retrospectively could lead to increased motivation to take part in the design process as users and also to establish synergies between users and designers. The usage of VR could further facilitate people to express themselves and their needs, resulting in enhanced convergent thinking and an improved design synthesis. Figure 1.3 shows a participatory design workshop in which participants helped the involved designers to derive and understand specific user needs for future public transport in megacities (Stadler et al., 2020c).

### 1.3.3 Develop

VR has been utilized in the *develop* stage for immersive prototyping and also evaluative activities such as usability testing. Especially in the area of hardware prototyping, VR is already being used to complement and ideally even replace traditional CAD applications such as Rhinoceros[2] and 3ds Max,[3] and research in this field is active to tighten the links between CAD and VR (e.g., Danglade and Guillet, 2022). Many researchers have already investigated the impact of VR and CAD within the design process (e.g., Akca, 2017; Stadler et al., 2020b). Research suggests that the main advantages are visualization and experience of realistic scales, realistic environments, engagement, and immersion. The major disadvantages of VR in this context are the lack of accuracy in developing high-fidelity prototypes, the lack of haptic feedback, and the limited field of view (FOV) for users while being immersed in VR (Stadler et al., 2020b). By comparing commercially


*Figure 1.3* Participatory design activities in VR to define user needs for providing information of autonomous vehicles to passengers (e.g., route, velocity, and system confidence).

available CAD applications (desktop-based) with immersive spline and volume creation applications (VR), researchers found that VR-based applications can promote an enhanced sense of scale, improved perspective when experiencing models, and increased usability. In addition, using VR to create models promoted excitement and engagement while designing (based on Stadler et al., 2020b). Beyond that, researchers found that 3D models become considerably easier to understand and experiencing these models becomes less demanding regarding spatial reasoning skills in VR, which significantly reduces learning curves (Coburn et al., 2017). Overall, even though a considerable amount of research is already conducted in the domain of using VR for prototyping, research still needs to expand in order to make VR a considerable tool for day-to-day prototyping.

Furthermore, VR has been used to evaluate design concepts including methods such as usability testing, experience simulation, and user testing (Martin and Hanington, 2012). Especially in application domains in which physical prototyping is time consuming and expensive, VR is often used for evaluation purposes. For example, a number of studies have developed VR simulators to evaluate communication concepts between autonomous vehicles and pedestrians at crosswalks (Stadler et al., 2019). The results indicate advantages of using VR in safety for participants and efficiency in terms of time and cost, as well as laboratorial conditions. Furthermore, scenarios could be visualized that hardly could be recreated in real-life conditions. Still, the VR experiences led participants toward authentic behaviors. In summary, the usage of VR during the *develop* stage has the potential to foster prototyping (e.g., basic CAD works) through the possibility to experience models in realistic scaling, facilitating better understanding of the product to be designed and through improved usability due to natural interactions. In addition, regarding evaluation purposes, VR has the potential to increase efficiency in terms of time and costs, flexibility in evaluating concept variants, and most importantly, ensure safety for participants during evaluative studies. Moreover, the usage of VR evaluations allows data collection in laboratorial environments supporting the collection of valid and reliable data. Figure 1.4 shows a participant during a usability test to evaluate communication cues between pedestrians and autonomous vehicles (Stadler et al., 2019).

### 1.3.4 Deliver

VR also finds applications in the *deliver* phase of the design process, including activities such as design reviews and immersive presentations. These activities are essential during the design process as vital decisions are made during these activities. Castronovo et al. (2013) evaluated immersive VR systems for design reviews. The researchers concluded that aspects such as immersion and overall value of the VR system were highly rated by reviewers and that using the technology for design reviews allowed users to interact with objects and the virtual environment in real scale and in a very intuitive


*Figure 1.4* Usability testing in VR to evaluate explicit human-machine interfaces as communication cues for pedestrians when crossing a road in front of autonomous vehicles.

way. Felip et al. (2020) compared product attributes of furniture presented both in a real environment and in VR, investigating differences as well as equivalences between the respective visualization tools. The researchers concluded that certain product attributes were rated higher when experienced in VR, indicating potential benefits of using VR for presentations and design reviews. De Freitas et al. (2022) found that the immersive technology can be beneficial for design reviews since VR provides the opportunity to experience products out of new and immersive perspectives that could lead to new insights. Furthermore, VR can increase team engagement, improve interaction, and make these interactions more intuitive. VR further offers the potential to increase efficiency in terms of cost and time (e.g., by partly replacing hardware prototypes for design reviews) and also increases safety for participants. Furthermore, the usage of VR for design reviews allows improved communication channels for geographically dispersed team members and allows enhanced data visualizations and interactions (based on Coburn et al., 2017). Limitations of using technology for design reviews include limited realism, latency issues, and potential communication problems between involved team members. In summary, the usage of VR during the *deliver* stage impacts the design process as new channels for communications and discussions are opened up. Furthermore, especially for geographically dispersed teams, the usage of VR for design reviews and presentations offers enhanced communication possibilities and perspectives. Figure 1.5 shows a product presentation in which an immersive VR demonstration was included in order to let the audience see how newly developed products could be used in a range of scenarios (Stadler, 2021).


*Figure 1.5* VR–supported product presentation of future guidance systems at transit hubs of autonomous public transport systems (e.g., via AR supported guidance).

## 1.4 THE IMPACT OF VR ON THE DESIGN PROCESS

As the previous assessment indicates, VR has the potential to impact the design process on several layers: professionals and other stakeholders, users, technology, and design.

### 1.4.1 The impact of VR on professionals and other stakeholders

On a professional level, past deployment of VR in companies revealed significant profit for many activities, including the development of new products and services, training workers in hazardous situations or on novel manufacturing lines, assisting operators for maintenance activities, healthcare management, or proposing new experiences for customers. VR has shown indeed to facilitate service and product development and its lifecycle management with sped-up yet enhanced decision-making, increased productivity, and reduced production time while reinforcing operators' safety, thus providing significant financial benefits (Balzerkiewitz and Stechert, 2022) (see also for example the report released by Capgemini in 2018[4]). If VR may be considered as a viable tool, it has however not to be forgotten that major technological challenges still need to be overcome (see Section 1.5). It remains also necessary to carefully investigate the actual benefit of the usage of VR in every stage of the design process, to invest rightfully in VR solutions.

### 1.4.2 The impact of VR on users

On the level of users, the utilization of VR during the design process has several impacts. VR potentially facilitates co-creative activities that involve users in the development, resulting in products that expectedly better fulfill user needs. Especially in this context, research has shown that the usage of VR not only helped users to better express their needs and wants and also fostered motivation of participation in the first place (Stadler et al., 2020a). Surprisingly, this fact not only applies for younger tech-savvy generations and also seniors. Nonetheless, VR also occasionally intimidates people due to bad experiences with lies in the past (e.g., roller coaster ride with a smartphone-based VR application with insufficient frames per second). Thus, it is essential that the technology of VR is made understandable to participants to alleviate the fear of it. Additionally, user-centered interaction techniques and locomotion need to be implemented to ensure successful experiences in co-creative sessions.

Beyond the mentioned impacts for co-creative design activities, the usage of VR during the design process also impacts the users on the level of the products that are designed. First, due to enhanced divergent and convergent thinking, a deeper understanding of the underlying problem as well as user needs can be derived by the designers. Furthermore, during creative activities, innovation can be fostered. And second, during the *develop* stage valid and reliable evaluations can be achieved thanks to VR with increased efficiency in terms of time and costs. Thus, VR could lead to products that better fulfill user needs and that have improved usability. Moreover, product development times could be reduced and product development costs could be decreased, resulting in more affordable products (Stadler, 2021).

### 1.4.3 The impact of VR on technology

On a technological level, research and development in the field of VR as well as its applications is progressing rapidly. Even though VR may currently be not yet considered a fully mature technology, the present study shows its current potential for professionals. As the technology matures toward an end-user product, more new application areas and use cases emerge, which expectedly could foster further basic research into the technology itself. In this regard, the present study indicates that VR could become a significant technology for conducting experiments and other types of data collection in the future. Thus, VR could have a major impact on scientific endeavors in the future, provided that the visualization technology of head-mounted displays (HMDs) and Cave Automatic Virtual Environments (CAVEs) evolves toward a human-like FOV and resolution. Although research in the field of haptic feedback for VR users is ongoing, it remains uncertain to this day to what extent and when it will be possible to recreate realistic haptic feedback in VR. This fact may limit the use of immersive technology for certain application domains. However, if experiments and further data collections do not require participants to experience haptic feedback (and perhaps a realistic FOV or resolution), VR already has the potential to facilitate the conduct of experiments (e.g., by increasing efficiency and providing novel visualization capabilities).

### 1.4.4 The impact of VR on design

This chapter demonstrated that VR has the potential to impact the design process, the involved designers and thus, design as a profession as well. It became evident that the usage of VR fosters divergent and convergent thinking, helps to better understand user needs and application fields, offers improved prototyping capabilities, and can be used for time- and cost-efficient evaluations in laboratorial environments, resulting in valid and reliable data collections. Beyond that, thanks to VR, geographically dispersed design teams are offered immersive collaboration and review tools. Due to the range of available hardware, designers have suitable VR devices at hand at any stage of the design process, allowing it to become a strategic tool for them.

The involved designers are impacted by the technology as the way of working and the application of the design activities could be altered. Since the development of VR applications usually requires interdisciplinary teams, the designers become dependent on expertise such as software development. Hence, the tasks for designers frequently shift from being creators toward being project coordinators. Still, designers need to possess increased basic knowledge in professions such as software development to allow effective collaboration with future design teams. Furthermore, during co-creative activities, the role of the involved designers shifts from being concept creators toward being facilitators who help people to express themselves and their needs. Thus, similarly to the introduction of CAD to the profession of design, VR could also be a next game changer for the profession. Its usage during design can foster innovation and allow more efficient ways of working. However, the focus of research and product development, especially in a technology-driven world, should not lie on the usage of particular technologies but on the end-user (i.e., human-centered design) (see Section 1.6). Thus, it is expected that VR could become another strategic tool for designers; however, the immersive technology will not replace conventional design methods. In order to allow a sustainable and effective utilization of VR in design-related professions, the usage of this technology needs to be taught in related professions to allow its usage for future designers.

## 1.5 LIMITATIONS OF VR

VR, although well disseminated, needs strong attention regarding its limitations. Indeed, its development is still hindered by inherent constraints, which may impact user experience, including for example distance and size perception, known to be usually deformed in VR (Renner et al., 2013), and by extension, lower the acceptance of these technologies. Here we provide several major limitations; however, an extensive list may be considered, for instance through a taxonomy to be formalized linked with the usage of VR and development opportunities.

First limitations are related to technical aspects. Regarding HMDs, most of the devices available on the market have a restricted FOV, around 110°, although recent devices can offer larger FOV. This limitation is compensated by a 360° field of regard. Other immersive displays, such as CAVE systems, can offer a larger FOV, close to the human one, but are limited in the field of regard, as screens have limited physical dimensions. The resolution of the displays may also represent a limitation. Although recent devices can offer up to 4K or even 8K resolutions, the higher the resolution, the higher the need for computational power. Another technical limitation relates to the rendering of stereoscopic images, including for example optical components of the displays, such as the optical lenses embedded in HMDs that usually introduce distortion of the images, or for large immersive displays, stereoscopy technologies, such as active and passive filtering and autostereoscopy.

Apart from technical aspects, other limitations are related to their usability and the well-known cybersickness effect. Regarding usability, as per the ISO 9241-11:2018 norm, VR systems should allow efficiency, effectiveness, and satisfaction (ISO). However, non-expert users often struggle to use VR technologies in each new application, as interaction in and with virtual environments usually requires the manipulation of interaction devices that are not natural by default. An emblematic example is navigation in virtual environments. Immersive displays impose physical constraints (e.g., cables, screen size, tracking area), thus limiting physical displacements. Therefore, natural walking is quickly restricted and must be replaced by unnatural walking, requiring the development of specific techniques, such as teleportation (Prithul et al., 2021) or controller based (e.g., Wang et al., 2019). However, such techniques necessitate optimal parameter tuning that can be time costly and may not fit all users, possibly leading to distraction from the original task, the occurrence of cybersickness effects, or cognitive overload (Xia and Wu, 2021), thus not fulfilling usability criteria. Solutions such as so-called redirected walking techniques, authorizing to physically walk indefinitely in a limited area by deceiving the brain (Fan et al., 2022), or physical devices such as omnidirectional treadmills (Lohman and Turchet, 2022), allow to partly overcome these issues. However, the former again requires fine parameter tuning and the latter demands space and money while not guaranteeing the same sensation of walking as in the real world. Therefore, it is of primary importance to make sure that VR systems do not require long habituation periods to start interacting efficiently, effectively, and satisfactorily within virtual worlds. Last, it is crucial not to overload interaction. Although past work has shown that multisensory feedback (e.g., haptics, sound) may enhance user experience (Wee et al., 2021), available multisensory devices such as haptic gloves can still be limited in terms of interaction accuracy, and may not be relevant to use for all tasks.

Another important aspect is cybersickness effects. There is no doubt now that VR systems may induce sickness effects with very variable levels of criticality (Kemeny et al., 2020). This phenomenon is highly complex to address in the view of effective usage of VR systems, as its mechanism is still debated and its occurrence depends on many parameters, including human-related characteristics, technological aspects, or application scenarization (Kemeny et al., 2020). Mitigation strategies represent a large piece of the literature on cybersickness; however they act more like patches and do not provide definitive strategies to solve this issue. Very recent work shows a tendency to refocus attention on the user and propose solutions to individualize interaction, with the help of artificial intelligence (AI) tools, with promising results (e.g., Wang et al., 2021).

## 1.6 GUIDELINES FOR USING VR DURING THE DESIGN PROCESS FOR PROFESSIONALS

### 1.6.1 Consider the actual benefit of the usage of VR

The success of design studies and product development does not solely lie in the usage of VR. At any stage of the design process and for any design activity it has to be considered whether the usage of VR involves specific benefits that outweigh its drawbacks. The development of VR applications involves a certain degree of complexity, usually addressed by interdisciplinary teams. If the usage of VR does not involve significant advantages, its usage might even impair design activities within the respective design process stage, especially considering the fact that conventional design methods already proved their value for design studies. Beyond effectiveness, it has to be considered that the development of VR applications also impacts the efficiency of process stages. Even though the usage of VR for concept evaluations can prove to be time- and cost-efficient, developing complex immersive applications especially in the early stages of the design process might be inefficient in terms of time and money spent compared to conventional design methods.

It is also worth noting that many companies invest in light VR systems, such as HMDs, as being thrilled by such technologies but never use them. A reason often mentioned is that they do not take time to study the usages of VR (i.e., they do not find utility at the moment), therefore, they do not develop internal expertise in VR to run these systems. As a consequence, there is a strong need to be accompanied by external VR experts to help define the usages, train people to develop internal skills, and then deploy VR efficiently according to advantages that could be taken from using VR.

### 1.6.2 Choose appropriate immersive displays

Once the actual benefit of the usage of VR is determined, setting up a VR system requires technological choices in terms especially of displays. Among existing systems, the most prominent ones are the powerwall, the HMD, and the CAVE. Each system is very different from the other in terms of characteristics and so in terms of price.

HMDs are quite accessible, with prices ranging from around 300€ for entry systems to 30k€ for the most advanced. The choice of the model depends on the activity to achieve. HMDs, as already mentioned in Section 1.5, allow 360° field of regard and fully immerse users, as they shield from reality. This last aspect is important to consider, as by default it prevents users to see themselves and other people, which may be inconvenient for activities for example involving colocalized collaborative work. Embodying users in a virtual avatar is further necessary to maximize presence in virtual environments, representing non-trivial additional work. Nonetheless, HMDs are well suited for activities in which designers can develop and rapidly visualize without the necessary help of coworkers. Thus, the usage of HMDs is especially useful for the early stages of the design process for creative design activities since the setup and usage of these devices involves little complexity and time. Here, depending on the design activity as well as the study context, even budget devices with three degrees of freedom can be sufficient. Alternatively, HMDs with high-resolution displays and six degrees of freedom are frequently used in later stages of the design process for evaluative activities. The advantages of these devices lie in their affordability and low complexity to set up and use. Still, due to their hardware capabilities, high degrees of immersion can be achieved, which can lead to the collection of authentic user behaviors. Moreover, high-performance HMDs are regularly used for design reviews in which one person is immersed in a virtual environment while other reviewers follow interactions via screen mirroring of the VR device. This allows reviewers to focus on discussions and design decisions rather than the interaction with the virtual environment.

CAVE systems are unique systems that are usually not available off-the-shelf but are rather custom made based on specifications. Indeed, contrary to HMDs, CAVE systems are usually made with large screens surrounding the users, of different shapes and sizes, which necessarily limits the space to physically move. A typical shape and size for such a system is a four- or five-sided cube of around three meters length per side. Virtual environments are displayed through video-projectors able to deliver stereoscopic images. Depending on the specifications (e.g., number of sides, screen size and material, projectors' frame rate, resolution, luminance and brightness, stereoscopy type, embedded tracking system), its cost may range between 50k€ and >1M€. Such systems are usually present in large companies or in academic institutions, some of them proposing to make them available to professionals.

Despite a lower field of regard than HMDs, its great advantage lies in its possibility for users to still see themselves and other people, which makes it particularly suitable for colocalized collaborative project review activities or concurrent engineering. This becomes especially interesting for design activities in later stages of the design process such as design reviews and immersive presentations, for instance before production commences, and past studies showed the added value of CAVE systems in design activities (Basset and Noël, 2018). The collaborative nature of CAVE systems in this context allows realistic and immersive experiences of digital content for whole design teams while not impairing communication and discussions. Some existing CAVE systems even allow to render stereoscopic images for several users at the same time with viewpoints adapted to each user. In terms of ergonomics, CAVE systems offer high comfort in usage since users only require to wear light glasses instead of heavy HMDs.

As an alternative, powerwalls, generally composed of either one large screen or several smaller screens put end to end, are less immersive than the previous systems, as the field of regard in the vertical plane is rather limited. However, these systems are well suited to collaborative sessions. Especially for team discussions and design reviews in later stages of the design process, powerwalls constitute an interesting alternative to CAVE systems and HMDs as they are mobile and flexible in use, require little space, and usually are less expensive than a CAVE. Similar to CAVE systems, powerwalls not only allow collaborative sessions between several team members and also allow the possibility to combine digital content with physical objects. Furthermore, since only light glasses are required instead of HMDs, powerwalls offer a high level of comfort while being used, knowing that they can be used in either monoscopic or stereoscopic mode.

In summary, depending on the design process stage and the activity and also aspects such as budget and involvement of team members, each of the three hardware solutions offers its own set of advantages and drawbacks.

### 1.6.3 Prioritize interactivity over representation

Ensuring a usable application is more important than its visual representation (e.g., by trying to achieve a high degree of realism). Users usually are able to accept a certain degree of abstraction while still experiencing a high degree of immersion. In this context, the term "willing suspension of disbelief" states that users temporarily believe something that is not true in order to enjoy a fiction.[5] This fact is also applicable to VR experiences. Here, users accept certain degrees of abstraction of the visual representations without questioning the whole VR experience, but VR experiences with insufficient usability are rarely successful. This fact shows the importance of user-centered design as well as usability, especially for people who have little to no experience with VR applications.

### 1.6.4 Choose appropriate interaction techniques

As mentioned previously, interaction (navigation and manipulation) techniques need careful implementation, as the usability of VR systems is at stake. The first aspect to consider is who will use VR and for what purpose. As we demonstrated in Section 1.4, the impact of VR will differ depending on the category of end-users: designers, professionals, stakeholders, and customers will have needs different from each other. Even within a category of users, needs may differ depending on the stage of the design process. If the usage of VR brings benefit (see above), and despite the availability of more and more products on the market, the choice of the technologies and methods relevant to the corresponding activity should be derived from specifications, with a principle that overloading interaction with complex techniques and devices is useless if the activity does not require it. For example, if the activity consists in verifying design elements at some specific locations in a large environment, locomotion in this environment could be performed by teleportation for example, rather than classical controller-based (e.g., joystick) locomotion or using physical devices such as treadmills, simplifying the design of the immersive application and its usage, while ensuring comfort of use. Likewise, if the activity does not require accurate gestures with precise feedback, it may be unnecessary to use complex haptic gloves but rather simply VR controllers or optical finger tracking. Therefore, the simpler, the lighter, the better.

This principle is all the more important to follow as users may not have the same degree of expertise in the use of immersive technologies, the best being to implement interactions adaptive to users and the context, which may require expert skills in VR technology implementation and in fields including artificial intelligence and neuroscience.

To be sure that the system developed answers requirements and fulfills usability, user evaluations may be conducted among a panel of users through subjective and objective means, such as questionnaires (e.g., SUS for usability, SSQ for cybersickness, NASA-TLX for cognitive load), performance measurements (e.g., activity achievement time, error rate), physiological and behavioral measurements (e.g., electrodermal activity measured in real time through wearable sensors,[6] eye gaze through sensors embedded in HMDs,[7] or through observations of users), and oriented or free interviews.

### 1.6.5 Avoid the exposure of technical limitations of VR

As it was pointed out earlier, the technology of VR involves a set of limitations, mostly of technical nature, such as restricted FOV or display resolution that does not match the human eye. Technical limitations like the aforementioned need to be carefully considered during the development of VR applications. If the designers decide to use VR for evaluative design activities, visualization realism (e.g., size, rendering in terms of color and contrast) needs to be kept in mind. This means that in VR, it could be harder to recognize objects in certain distances than in real life which retrospectively could impair the validity of evaluative data collections. This fact also applies to the FOV. If for instance the usability in aircraft cockpits is evaluated with VR including eye-tracking, it has to be considered that the FOV in VR is different compared to the human eye. Thus, VR experiences that expose such limitations and impair data collections should be avoided.

### 1.6.6 Minimize cybersickness

We exposed earlier the occurrence of cybersickness as being one major limitation of VR technologies. This phenomenon should particularly be well considered before deploying VR in design processes. Since many factors can influence its occurrence and severity, these should be carefully reviewed, and mitigation strategies be accordingly implemented. From the technological viewpoint, for example:

- ensuring minimal latency in the whole system (between the user command and the response of the system) (Porcino et al., 2017);
- optimizing virtual applications, especially 3D models, to provide at least 60–90 Hz frame rates;[8]
- well-adjusting immersive displays to the eyes, including the position of the device, parallax, and the inter-pupillary distance (physically and by software), which also affects distance perception (Woldegiorgis et al., 2019);
- well designing immersive scenarios (Lo and So, 2001);
- optimizing interaction (i.e., choose appropriate interaction methods and devices – see above – and tune interaction, especially navigation, parameters according to the needs, the context, and users). Particularly for virtual locomotion not based on teleportation, it is advisable to avoid abrupt accelerations and decelerations, keep below specific acceleration thresholds, and maintain navigation speeds close to natural speeds (Terenzi and Zaal, 2020);
- implementing dynamic FOV restriction (Teixeira and Palmisano, 2021) or blur effects (e.g., Chen et al., 2022);
- using salient visual references (e.g., a static grid (Kemeny et al., 2017)); and
- implementing motion platforms (e.g., Plouzeau et al., 2017) or vibratory stimulations (Lucas et al., 2020).

From the human-related viewpoint, for example:

- limiting immersive exposure time, as the longer the exposure, the more likely the occurrence of cybersickness (Garrido et al., 2022). It is often recommended not to exceed 10 minutes of exposure. When a user starts reporting sickness, it is mandatory to immediately quit the VR experience and let him/her rest. It is also advisable after longer exposure to avoid for example driving;

- avoiding repeated exposure in the same day, as cybersickness effects are cumulative;
- avoiding exposure for sensitive users, e.g., pregnant users or suffering from epilepsia;
- considering users' profile (e.g., gender, age, past experience with VR and video games) and individualizing interaction according to the proneness to cybersickness (e.g., Wang et al., 2021); and
- adapting interaction to the real-time user's physiological state (Plouzeau et al., 2018), which requires however to wear physiological measurement devices.

## 1.7 CONCLUSION

VR technologies, being more and more widely spread in many domains, are changing the way we work. In this chapter, we have shown that the usage of VR has the potential to greatly impact the design process, with tangible advantages and benefits. We also stressed out that despite such enthusiasm, professionals have to consider important limitations still existing, and that challenges need to be overcome for VR to be established as a strategic tool during the design process. We have listed several of importance. However, if these challenges and limitations are taken into account carefully, with clearly identified specifications for the immersive applications, VR can provide with more effectivity and efficiency along design processes. To help professionals overcome such limitations and perform successfully with VR during design processes, we have proposed a general set of guidelines, based on past literature and experience. As a non-exhaustive selection of representative VR case studies was chosen in the present investigation, the generalization of the proposed guidelines is naturally limited. Thus, these guidelines need naturally to constantly be revised and enhanced, as research and development advance in this field, and VR is further adopted on longer periods than those usually described in the literature. To further objectify the investigation and guidelines, the derivation of a taxonomy of using and evaluating VR is planned as a next step.

As these technologies progress, interesting insights may be considered for professionals in the design field. First, considering further human-centered approaches in VR might help designers better appropriate these systems. We have already mentioned recent work proposing to integrate artificial intelligence tools to predict the occurrence and severity of cybersickness; such tools could be used to predict the designers' intentions and help them conduct design activities, the idea not being to replace them but on the contrary to further stimulate them, for example during ideation sessions. Still, similar to one of the proposed guidelines, the usage of AI should result in a significant advantage over conventional methods to justify its usage, and further studies should be conducted to prove its concrete effectiveness. This chapter demonstrated that the immersive technology of VR has the potential to foster divergent and convergent thinking, facilitates co-creative activities, and offers advantages in prototyping and concept evaluation, as well as design reviews and immersive product presentations. With these enhancements, VR has the potential to become the next disruptive game changer for design-related professions by directly impacting the design process and altering the future roles of the involved designers, as well as enhancing the whole profession of design.

## NOTES

1 The term “product” in the present chapter includes systems, experiences, and businesses.
2 Rhinoceros (2022), https://www.rhino3d.com/ (Accessed: 25.07.2022).
3 Autodesk, 3ds Max - 3d Modeling and Rendering Software for Design Visualization, Games, and Animation (2022) https://www.autodesk.com/products/3ds-max/overview (Accessed: 25.07.2022).
4 Capgemini, Augmented and Virtual Reality in Operations: A guide for investment (2018), https://www.capgemini.com/us-en/augmented-and-virtual-reality-in-operations (Accessed: 25.07.2022).
5 Oxford Dictionaries, “Suspend Disbelief.” https://en.oxforddictionaries.com/definition/suspend_disbelief. (Accessed: 25.07.2022).
6 An example of such device is the Empatica E4 wristband: https://www.empatica.com/en-eu/research/e4/ (Accessed: 25.07.2022).
7 Examples of HMDs integrating eye tracking sensors are the HTC Vive Pro Eye, Varjo’s HMDs, the Pico Neo 3 Pro Eye.
8 https://docs.unrealengine.com/5.0/en-US/xr-best-practices-in-unreal-engine/ (Accessed: 25.07.2022).

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