## Abstract

Virtual reality (VR) has become an interesting tool in many research fields, and benefits have already emerged. Thus, in recent years VR is also being used in sport science and sports practice. With this, controversial results and often existing preliminary study designs make it hard to explain why differences in user's actions still occur within VR compared to real-world (RW) conditions. One of the reasons might be the artificial presentation of the virtual environment leading to differences since VR does not fully measure up with natural conditions. Hereby, the most stimulated sense within VR is the visual one, although others can be stimulated. Accordingly, the question is whether differences in user's visual perception occur within virtual environments and how this may affect the users' actions. Therefore, more research should be done to address this problem and narrow down the influencing factors. In the current work, basic skills in VR are compared with those from RW to recognize more specific differences and recommend how VR can be used nowadays within the sports sector, also enabling transferable performances. Hereby, the focus is predominantly comparing the visual perception between the conditions (RW and VR). The comparisons relate to 1) the measurement quality of gaze behavior on static and dynamic visual stimuli, 2) the spatial orientation including distance estimations, route recreation, and actively walking tasks and 3) the completion of motoric tasks (balancing, grasping, and throwing) accompanied with different body visualization types to examine which body parts need to be visualized during the VR experience to fulfill adequate performances. Summarized, there occur marginally differences within the parameter collected in both conditions. For the gaze behavior, less precision is provided of the integrated Eye-Tracking system in the head-mounted display. Furthermore, the participants could not observe the dynamic stimuli in VR as accurately as in RW ($p<.05$). Within the spatial orientation, only in route recreation has been found an impact in VR, however, the actual task demand was equally fulfilled. Examining the body visualization, the worst performance occurred when no body was visualized during task completion. However, the remaining body visualization types did not significantly impact participants' performance, so whole-body visualization is not essential for completing motor tasks in VR. Overall, the participants' performances are comparable to those from RW. Although slight differences have been shown in VR in terms of longer movement execution time and increased subjective estimation of tasks' difficulties during the motoric tasks, there are no limitations affecting participants' performances within basic skills. Further investigations could reveal whether VR can already serve as an additional or alternative training tool in sports.

**Contents**

**List of abbreviations**

| | |
|---|---|
| 1PP | first-perspon perspective |
| 3PP | third-person perspective |
| AOIs | Area of interests |
| CAVE | Cave Automatic Virtual Environment |
| cm | Centimeter |
| CPU | Central processing unit |
| CS | Cybersickness |
| EEG | Electroencephalogram |
| EGG | Electrogastrogram |
| ET | Eye Tracking |
| FBX | Filmbox data |
| FoV | Field of view |
| FR | Foveated rendering |
| GB | Gigabyte |
| GPU | Graphical processing units |
| GS | Gaze system |
| HMD | Head mounted display |
| IPD | Interpupillary distance measurement |
| m | Meter |
| M | Mean |
| ms | Milliseconds |
| MS | Motor system |
| NB | No body |
| NF | No feet |
| NH | No hands |
| NHA | No hands and arms |
| NLF | No leg and feet |
| POR | Point of regard |
| PV | Peripheral vision |
| RW | Real world |

| | |
|---|---|
| s | Seconds |
| SD | Standard deviation |
| SSQ | Simulator Sickness Questionnaire |
| VA | Visual attention |
| VAC | Vergence accommodation conflict |
| VE | Virtual environment |
| VM | Visual memory |
| VR | Virtual reality |
| VS | Visual system |
| WB | Whole body |

## List of Figures

## List of Tables

# Chapter 1

**Introduction**

In our daily life, humanity is confronted with issues complicating the regular course of the day. The workflow must be made more effective and efficient, resulting in more time to comply with family, friends, or free-time activities. The progress of sophisticated and innovative technologies supports improving life quality (Li & Perkins, 2007). Currently, many companies such as Sony, Samsung, HTC, Oculus, Google, and recently Apple, make massive investments into virtual reality (VR) (Ebert, 2015; Korolov, 2014), and user and researcher become attentive to their specific interests (Cipresso et al., 2018). A survey shows that the population's interest (age of sample over 16 years old) in VR applications has more than doubled in the last two years (Klöß, 2020). Due to the high demand, VR is applied in many different fields, such as medicine (Bernardo, 2017; Pfandler et al., 2017), informatics or computer science (Luidolt et al., 2020; Olade et al., 2020), psychology (Cohen et al., 2020), rehabilitation (Prasertsakul et al., 2018), sports (Neumann et al., 2018), and innumerable others. VR systems have vast potential to be used as a tool that positively affects the interests of humanity in varied different ways, such as an easier implementation of online meetings or video teleconferencing (Thies et al., 2018), autonomous training or learning without relying on an accompanied personal trainer (Hülsmann et al., 2018; Kwon, 2019) with higher motivation during exercises (McClure & Schofield, 2020), acting out hazardous situations without real danger (Rory M.S. Clifford et al., 2018) and furthermore.

Among all the fields of application mentioned above, VR arouses particular interest in sports science usage lately. Through the benefits of the development for mobile use (wireless systems) and the increased computational power facilitating a more realistic feeling of being present in the virtual environment (VE)[1], the inclusion of this system into different kinds of sports multiplies. Besides, the implementable integration of multisensory stimulation establishes a connection to natural conditions that support the transfer of VR adapted skills into real life (Bowman & McMahan, 2007). Therefore, VR already has been used to train sport-related skills in a tremendous variety such as in dart (Tirp et al., 2015), baseball (Gray, 2017), karate (Petri

[1] The term VE represents the virtualized surrounding that the user can perceive. The term VR instead considers the superordinated system, including all hardware and software components, which enable the perception of the VE.

et al., 2019), or competitive sports in general (Wang, 2012), basketball tactics (Tsai et al., 2017), and rowing (Parton & Neumann, 2019), etc. For getting a more profound impression of the usage of VR in sports-related training scenarios, a previous compilation of studies provides an overview of today's possible practical involvement (Neumann et al., 2018). A brief summarize of the current usage of VR during sports is also presented later in this work.

Apart from the previously described usage, integrating VR into sports should be considered as an additional training method and should also be in conjunction with autonomous individual training at any desirable location (home-based VR training) (Sheehy et al., 2019). Different hardware systems such as gaming laptops providing high computational power and battery-operated VR systems ensure high portability and facilitate multifunctional usage opening new applications fields. Previous findings also advocate using VR in terms of stand-alone training independently from external sources for medical and traumatic emergencies (Couperus et al., 2020) or physical education (Zhang & Liu, 2016). Zhang and Liu (2016) emphasize that VR ensures immersive feelings and experiences and generates a better knowledge of sports-related skills by interactively practicing.

Despite the increased usability, functionality, and application of VR systems, it is crucial to examine how new technologies affect the user (Malathi Srinivasan et al., 2006) and what kind of differences may occur during training in a VE since the stimulation of the human nervous system takes place artificially. To recommend VR to its full extent, it should have been tested and evaluated to ensure smooth participation and avoid unexpected occurring adverse effects of cybersickness such as nausea, dizziness, fatigue (LaViola, 2000). Further analyses could reveal prerequisites needed for the user's successful interaction within VEs, e.g., the graphical requirements, the visualization of the user's body, the generation of feedback of the individual actions, etc. VR is often recommended in its possible application after simply testing specific motor skills. In contrast, examining basic skills fundamental for every action or sports performance is either neglected or even avoided. Furthermore, previous studies show that VR performances, in general, cannot keep up to the full extent with those from the real world (RW) (Pizzi et al., 2019; Rau et al., 2018). The question remains open about what causes these differences and whether VR can be used without hesitation in all areas, especially in sports.

Therefore, the current work takes a step backward and focuses on evaluating the usage of the VR system keeping in mind sports-related training and learning scenarios. The controversy of experimental results and the conduction, including preliminary study designs, makes it hard to undoubtedly endorse the transfer of VR adapted skills into real conditions. Many factors may influence participants' performances within VEs. It is crucial to determine them, making further recommendations and improvements of the usage of currently developed VR systems. One of these factors affecting the performances may be the artificial stimulation of the visual perception within VR since the most crucial information is received through visual processing.

Considering the status quo of integrating VR into a sports-related context, the application is not starting from scratch. A positive aspect is that a lot of work has been done using the benefits of VR, and training or learning tools are already established for different purposes. A simultaneous problem arises when companies promise possible application fields without being aware of resulting consequences due to not thoroughly evaluated VR technology. An evaluation of VR concerning different participants' behavior elicited through the artificial visualization of the three-dimensional space could reveal crucial facts which should be recognized within the development and further integration into the sports field.

During the interaction and exploration of our environment, the visual system plays a crucial role in extracting valuable information helping us to complete daily tasks. Especially in sports, the visual system is a prerequisite facilitating complex movements or reacting on objects, teammates, opponents, etc. To verify VR for its usage in sports, the current work's goal was to examine whether the visual perception within virtual environments is comparable to RW. This is realized by comparing participants' performances within different tasks conducted in RW and VR, requiring adequate visual information processing to be successfully executed. Those performances relate to basic skills needed as a prerequisite in the majority of sports. Thereby, all presented investigations have been carried out with special consideration of the visual perception, although other sensory input can be provided through the current VR devices, such as auditory via headphones or haptic feedback elicited through the supplied motion controller or wearable soft robotic gloves (Jadhav et al., 2017). Comparing the visual perception in RW and VR includes several studies that were designed and split into three different sections described below. For each study, different parameters reconnected to the quality of visual perceptional processing within the conditions (RW and VR) are chosen and compared. In addition, the relevance of all sections for sports is discussed, and possible integrations are concluded. Within each section, different studies are included, thematizing the comparison of various participants' task performances between RW and VR.

In the first section, the presented study contains how valid the visual perception is measurable within VEs compared to real conditions. Therefore, a comparison of the measurement quality between the integrated eye-tracking (ET) system in the head-mounted display (HMD) and the conservative mobile ET glasses was made (Pastel, Chen, Martin et al., 2020). In addition, it reveals how accurate the participants could observe visual stimuli in VR. Related to this, ET has been evaluated as a great tool to reveal information about the individual's visual behavior by extracting gaze parameters, such as fixations, saccades, etc. (Alemdag & Cagiltay, 2018). This study's goal was to examine whether the stimuli presented in VE could be accurately fixated and how precise the integrated system captured gaze data over time compared to the mobile one used in RW. The results give an insight into the creation of algorithms to detect the visual perception relying on the quality of extracted raw data relates to the same extent within VR compared to RW. Furthermore, the combined technic (HMD and ET) has immense potential to develop further implementations to improve VR usability and interaction methods (Meena et al., 2019; Sidenmark & Gellersen, 2020). Those implementations could also be important for sports-related purposes, in which they enable new forms of interaction, visual attention measurements, or infinite walking methods.

The second section concentrates on the ability to orientate within VR since accurate walking or interaction should be guaranteed concerning transferred skills from VR to RW, not only related to sport-specific performances (Pastel, Chen, Bürger et al., 2020). Hereby, the participants estimated verbally and through walking different distances, maintained a route that should be recreated by memory, and underwent active walking tasks requiring rotation and translation accuracy. The study's goal was to examine whether visual information processing takes place at the same degree in virtual compared to RW conditions. This was realized by letting the participants first observing each environmental condition. Afterward, various tasks were completed, accompanied by a covered vision to rely on the previously collected information during the observation. To minimize the influence of different inter-individual levels of visual memory and ensure that the performances are related to the quality of the visual input during perceiving each environment, the participants started directly after the vision was covered with a blindfold (or the screen was blacked in VR). The primary goal is to see whether the participants were aware of the objects' arrangement in the real and virtual scene and how accurate they could move towards them. Subsequently, further references concerning the meaning for sport-related purposes are made.

In the third section, the importance of visual body perception is examined by letting the participants conduct different sport-motoric tasks during a stepwise reduction of the body limb visualization. Possible influences on participants' performances are crystallized to make further recommendations on how much of the body must be perceivable to complete sport-motoric tasks in VR (Pastel, Chen, Petri, & Witte, 2020). In general, it is crucial to check whether motor performance can be completed adequately at all within VR, even when no virtualized body is visualized. In addition, concerning the practical use of VR-training scenarios, it is fundamental to examine whether a whole-body visualization must be generated to realize an adequate transfer of adapted skills into real conditions. Due to controversial results or missing examinations, it is still unclear which body part(s) need(s) to be visualized, helping in task completion, and whether the tasks are still executable when no-body visualization is provided.

Each result provides information about the comparison between participants' performances depending on visual perceptional processing in the RW and VR and what problems may occur regarding sport-related usage accompanied with this technical equipment. The following graphic shows the procedure of the current work and reveals the main research directions.

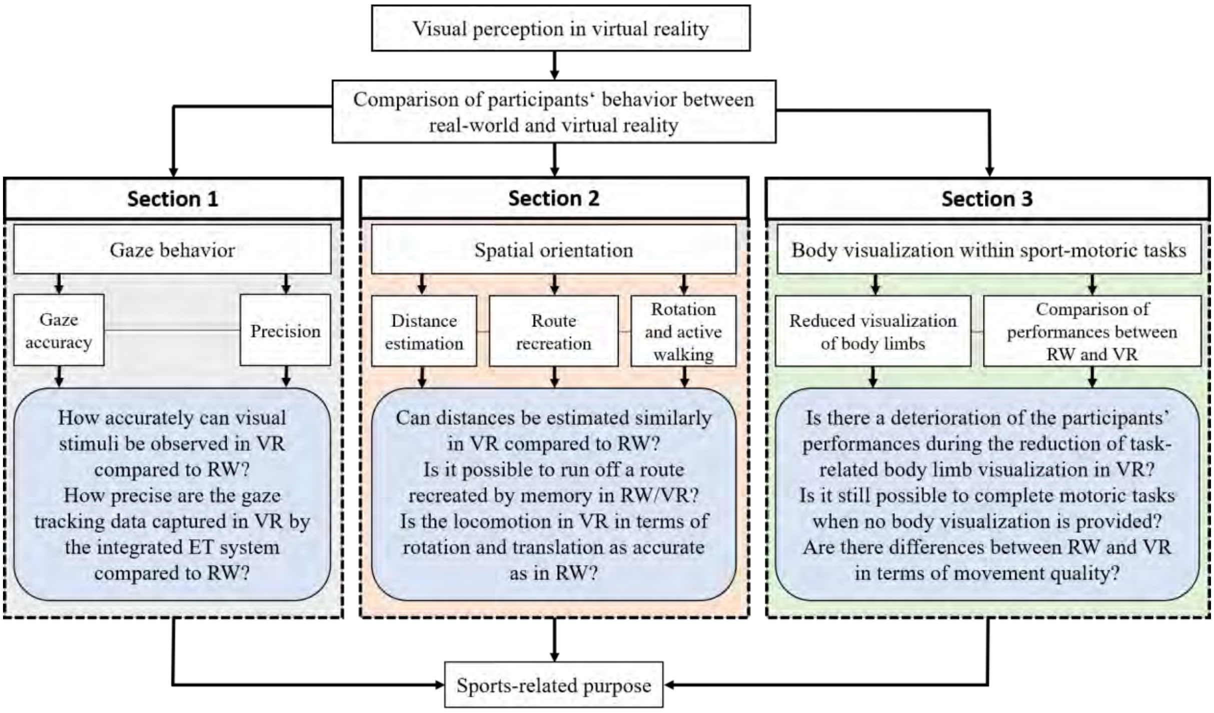


**Figure 1** An overview of the workflow of the current work. The overall goal is to examine the visual perception in virtual reality (VR) with subsequent comparison to real-world (RW). This is completed by comparing participants' behavior within three main sections (different colored boxes). The blue fields within the colored boxes indicate the upcoming questions answered after results compilation. In the end, a clarification of today's usage of VR in the field of sports is made. Further recommendations considering the VR system's prerequisites are provided, and upcoming ideas for new applications are collected.

# Chapter 2

**Theoretical Background**

The current work's goal is to evaluate the VR application for sports-specific purposes based on visual perception analysis. To ensure a better comprehension of the determined objectives and simplify the listed results being discussed later, essential information about all components included in VR is presented, and problems that may appear working with those technics are discussed in the following chapters. Currently, many definitions of VR exist, and the software and hardware components differ within those systems. Therefore, it is inevitable to specify the technical equipment used in the studies due to the fast development of hardware components and software engineering processes (Burdea & Coiffet, 2003).

## 2.1 Definition of virtual reality

In general, all definitions of VR include the activation of the sensual input within VEs. The creation of a perfect VR can be realized through the generalization of multisensory stimuli perceived by the user (Dörner et al., 2019). The stimulations of senses rely on three-dimensional content enabled by computer graphics using stereoscopic techniques. This can be provided by input and output devices (Zhang, 2017), allowing the user also for interaction (Seibert & Shafer, 2018; Zhao, 2009). For example, the HMD is considered as an output device because it stimulates vision, the most dominant sense for the human being to extract valuable information from their surroundings, even if one should not disregard the other senses (Hutmacher, 2019). As input, the integrated sensors or tracking systems (gyroscope or accelerometer) registering information coming from the RW, such as head-rotations or body translations. Other implementations allow using language or gesture also as input to command or interact within the VR (Preim & Dachselt, 2015). A further system is needed for transferring data between input and output devices in sequence for completing the setup. Due to the fast development, the authors provide an overview of the available software and hardware components (Anthes et al., 2016).

However, VR should not be reduced on its' technical level. In Dörner et al. (2019, p.13), Steve Bryson's statement is mentioned amplifying the comprehension of VR, which is defined as the usage of three-dimensional displays and interaction devices to explore real-time computer-generated environments. Therefore, the interaction within VEs is emphasized and well connected to the human-machine interaction.

Strongly connected to VR is the term VR system, which includes several components such as software, hardware, the surrounding physical world, and the human user providing all together the immersion into an entirely computer-generated environment (see Figure 2). LaValle (2019) emphasizes the importance of including the user in a VR system since integrated sensors track human motions. At that point, the user's vision needs to be adjusted in real-time to ensure high immersion. The real physical world always provides other stimuli perceivable of the user during the VE perception, such as acoustic, haptic, and even own body movements. Therefore, it is crucial to include the real physical world in the VR system as well (LaValle, 2019). When those components are fulfilled, and the user feels belonging to the VE, the term mental or virtual experience appears, indicating the acceptance of being in the full computer-generated environment. The experiences may differ from real-world condition due to changes in position in space and perspectives, additional linked data sets, different scales and further more (Edler et al., 2019).

The previously described components are widely available in the marketplace, and one can expect a rapid development of performance and higher demand due to costs decreasing and extended practical application (Wei, 2019).

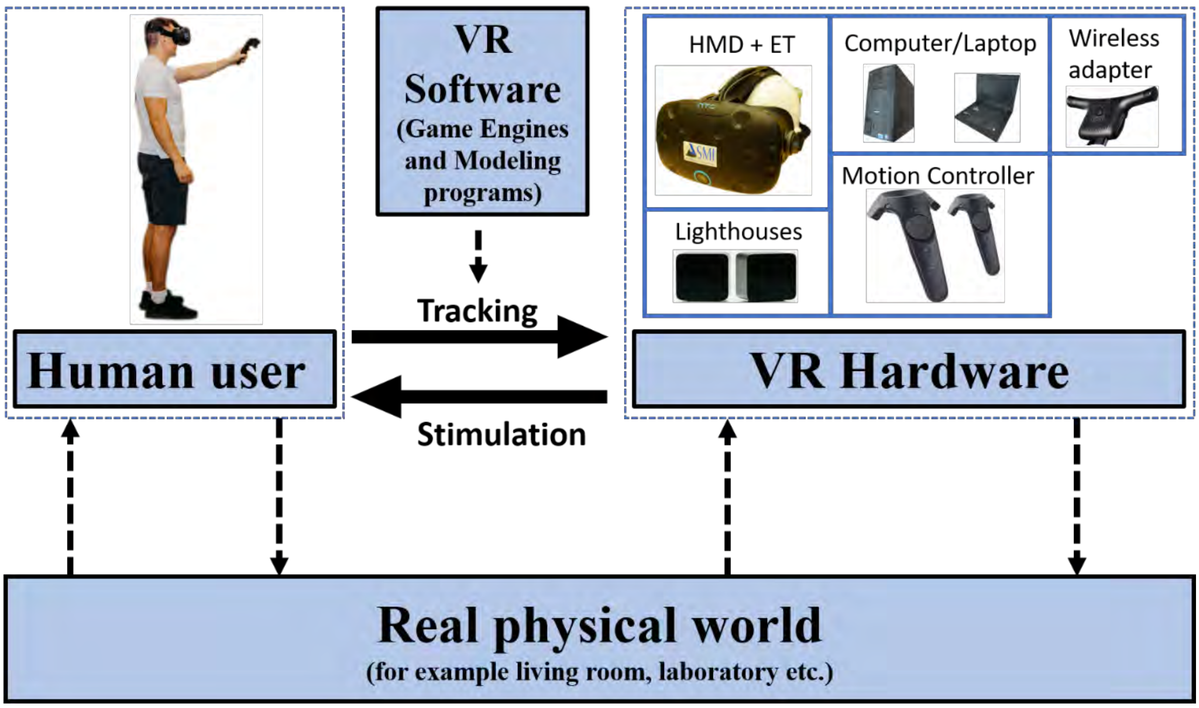


**Figure 2** Overview of all components included in a VR-system inspired by LaValle (2019, Figure 2.1, p.40). This graphic should serve as an example of a VR-System construction since not all of them have included an HMD (and ET), the lighthouses, the motion controller, the wireless adapter enabling free moving, or even a computer/gaming laptop.

The high amount of existing available devices and software leads to a short description of the components used within the conducted experiments. Therefore, the collected data is more comparable and useful for other researchers working with the same technical features. Previous findings show that heterogeneous systems may differ, for example, in working range or accuracy (Borrego et al., 2018), objective usability (Maraj et al., 2019), cybersickness (Yildirim, 2020), satisfaction scores (Shelstad et al., 2017), as well as in performances such as pick-and-place tasks (Suznjevic et al., 2017) or pitch and yaw movements (Lubetzky et al., 2019), and further. To better understand the outcome of the presented studies and comprehend future realizable VR applications, it is necessary to get a short overview of the current software and hardware features used in research and private uses. This generates a better imagination of possible integration into sports and which limitations may occur due to technical hardware components, such as weight of HMD or tracking area. Furthermore, the definition of VR depends also on its technical components realizing the visualization of the VE, since different possibilities occur working with, for example, different input and output devices for interaction or using stationary or mobile systems.

### 2.1.1 Software

At the current time, many modeling programs (3D Builder, Blender, BlocksCAD, etc.) and game engines (Unity3D, Unreal Engine, etc.) are provided costless, accomplished by a vast number of online manuals and tutorials helping to use them for one’s purpose. The software library serves already simple functions, which reduced complicated developing processes, but it is still a long way from having software that automatically generated VEs. Therefore, a basic understanding of VR fundamentals is a prerequisite to integrate it into research.

#### Blender

Blender (Blender Foundation, Netherland) is a 3D graphics software that allows to model, texture, and animate virtual objects and is suitable for all platforms, such as Windows, Linux, macOS, etc. It enables to realize realistic looking or more fictional virtual scenes (see Figure 3). Beck (2018) gives an overview of all integrated functions and provides a good start and advanced knowledge to construct individual designs.

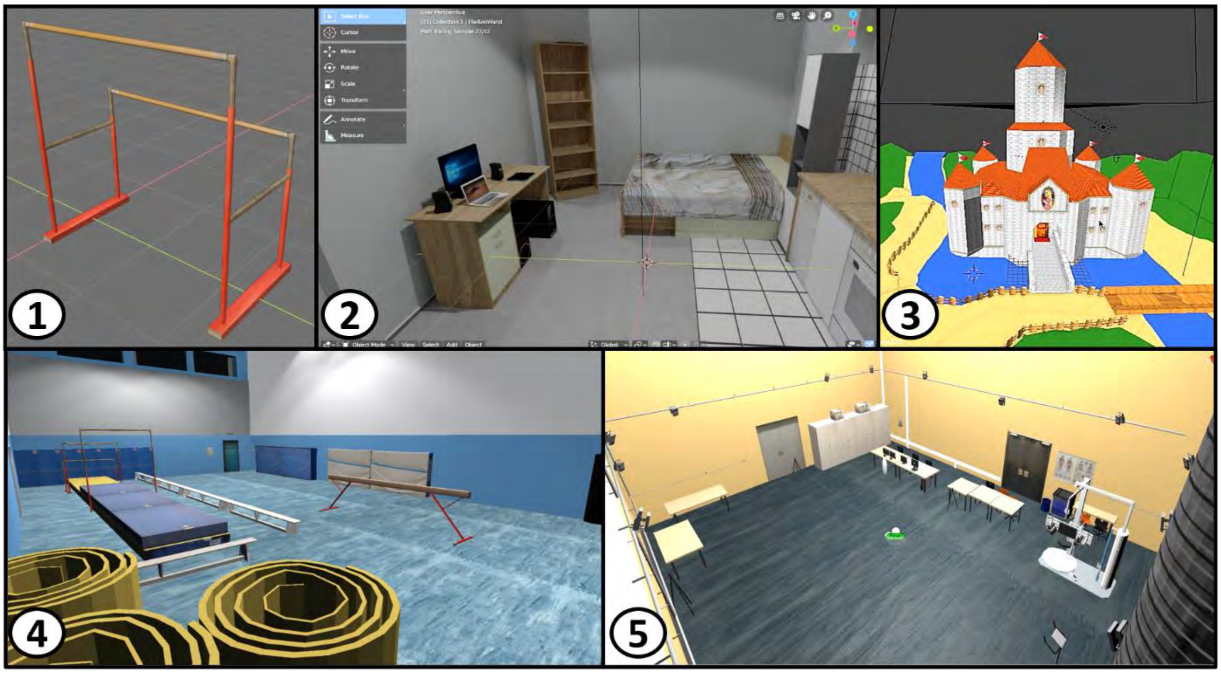


**Figure 3** Examples for the creation of realistic-looking virtual objects (1) or scenes (2), more fictive virtual environments (3), sport-related virtual environments (4), and virtual laboratory (5 – this virtual laboratory was created by Chien-Hsi Chen). In (2), higher hardware performances are required to run the scene without interruptions due to more included realistic components such as shading, lighting, textures, modifiers, and physics, etc. compared to the others. During the research, a smooth process is ensured through lower graphical components, whereas active walking and ways of interactions were prioritized since high immersion should be maintained during the conduction.

In the current work, the scientific purpose is to compare participants' behavior between the RW and VR. In the included studies, the participants had to complete various tasks under real and virtualized conditions. Therefore, all created testing rooms contained the same order of magnitude for all existing objects within the scenes by obtaining the sizes and designing the textures. Previous findings suggest to realize realistic conditions within VEs to ensure natural users' behavior (Brand et al., 2016). The shape of each object consisting of interconnected points (vertices), edges, and faces was created, and the associated textures were overlaid on the two-dimensional surfaces (UV-Mapping) (Beck, 2018). The lighting conditions were adapted to the real testing room awaking a more realistic impression of the VE. The priority was to create a smooth computer-generated environment without appearing interruptions elicited by insufficient performance of the graphic card, the working memory, or the central processing unit (CPU) (hardware components in a VR System, see Figure 2).

Unity

Unity (made by Unity Technologies, United States of America) is a development environment for creating and designing originally intended computer games. Unity projects can also be used for learning and training purposes (Theis, 2018). Unity offers the visualization of VEs, but it also provides the opportunity to interact with objects existing in the scene by implementing scripts from Visual Studio written in C# programming language. The increased development of computer games within the last few years offers various possibilities to examine users' actions within VEs and is, therefore, a suitable tool for scientific purposes. Furthermore, developed contents from Blender can be easily transferred into Unity-created scenes. Exported Filmbox data (FBX) are saved as prefabs containing the necessary information, such as materials, textures, physics, armatures etc., making them attractive for the modeling process. The preprogramming ensures high experimental control, and therefore, a standardized sequence of, for example, the presentation of visual, auditive, or haptic stimuli adapted to the user's actions. Another benefit of this software is the cooperation with others like Vicon Nexus (Pastel, Chen, Bürger et al., 2020), Vicon Shogun (Pastel, Chen, Petri, & Witte, 2020) (both developed by Vicon Motion Systems, United Kingdom), or for integrated ET-systems, by using predeveloped plugins by SMI (iViewNG HMD Api Unity Wrapper) (Pastel, Chen, Martin et al., 2020). To realize additional tracking of user behavior, infrared systems are often used (Merhav & Wolbers, 2019). The manufacturers provide tools allowing easy integration of hardware and software for both systems (VR and infrared-based tracking Systems).

Vicon Nexus and Vicon Shogun

Nexus is the Vicon (United Kingdom) software package for life science motion analysis enabling data acquisition, automatic or manual data processing and, management[2]. The versatile use of this software allows movement analysis, clinical gait, biomechanics, etc. In the current work, this software was used to capture participants' positions by using the motion capturing system (described in the following chapter) to compare the performances made in RW and VR. Although both systems (Motion Capturing and VR) used in the current studies emit infrared light pointing to a specific area for precise determination of the user's position, no interferences occur, and simultaneous usage can be realized.

Since one of the study's aims was to examine possible influences on participants' performances during a reduced visualization of different body parts, Vicon Shogun was used to track participant's bodies in real-time and transfer the position of the individual body limbs to the skeleton of the virtual avatar. Vicon Shogun is characterized by its robustness and fast, practical application. In addition, the software allows to record animations (for example, sport-specific movements), which can be reedited in the post-processing method. Those animations can be further transferred to humanoid avatars allowing realistic translations or rotations. Moreover,

[2] The official homepage of Vicon provides additional information: https://www.vicon.com/software/nexus/

the real-time tracking can also be generalized for virtual objects ensuring haptic feedback during the VR experience.

### 2.1.2 Hardware

Virtual Reality Systems (Glasses, Lighthouses, Controller)

For the VE visualization within the experiments, the HTC Vive (for Study 1) and the HTC Vive Pro Eye for the others were used. The HTC Vive (HTC, Taiwan) is the older model (2016) and presents the images with a resolution of 2160x1200 pixels (binocular) with 90 Hz. The Field of View (FoV) is around 110°. The whole system[3] is cable-based (5 m) and directly connected to the computer (in- and output device). Two motion controllers and lighthouses are integrated, ensuring interactions and accurate positioning tracking. Due to its limitations, the older model was used within the ET study, in which the participants were seated in a fixed position, and no movements were required during the experimental process (see Figure 6).

The HTC Vive Pro Eye (HTC, Taiwan, 2018) was used during the other studies. One of the main advantages was the wireless adapter, which realizes task demands with a higher range of motion and facilitates rotations without feeling restricted by a cable. The resolution increased (2880x1600 pixels, binocular), but the refresh rate and the FoV remain the same as the predecessor, as well as the number of motion controllers and lighthouses. The installed sensors are SteamVR Tracking, accelerometer, gyroscope, distance sensor, interpupillary distance measurement (IPD), and eye-tracking. Two lighthouses were used to ensure positioning tracking in real-time. The manufacturer specifies a size of spatial interaction field of 100 sqm using four lighthouses, whereas the standard number provides positional tracking in a 7x7 m area. Foveated rendering can be used to reduce the graphical processing units (GPUs), improving the performance and the quality of visualization.

Eye-Tracking Systems

Within the ET study, the SMI mobile binocular Eye-Tracking Glasses 2.0 (SensoMotoric Instruments, Germany) with a resolution of 1280x960 pixels and the sampling frequency of 60 Hz was used to track participants' eye movements in RW. Since the installed eye-tracker in the HMD (HTC Vive) was produced by the same manufacturer at the same manufacturing date, it is possible to compare the gaze behavior between RW and VR, and the emerging differences are not related to the different technical performance of the ET systems.

[3] All information was obtained from the official homepage of Vive: https://www.vive.com/de/

Motion-Capturing-Systems

For tracking participants' position and calculating distances for objects to be reached, an infrared motion capturing system (Vicon, United Kingdom) was used to track the three-dimensional passive markers placed on the participants' body. Thirteen cameras captured the movements with a high sampling rate (200 Hz), ensuring no positioning tracking loss during the conduction.

Computer Systems

Overall, two computer systems (source and target) were connected directly via an internet cable to generate smooth conduction of the studies. The first one (target) provided the simulation of the VR equipped with Intel i7 CPU, 16 GB memory, 512 GB SSD, and Nvidia GTX 1080 8 GB graphic card. The second computer (source) mainly presents the data for motion capturing (Nexus and Shogun) and consisted of an Intel i7 CPU, with 32 GB memory, 512 GB SSD, and a Nvidia Quadro K2200 4 GB graphic card.

All these technical components contribute to the VR system, allowing the creation of an interactive, realistic-looking, and immersive VE. Since the definition of VR includes the activation of the sensory input of the user, it is fundamental to list all senses which are mainly stimulated within the VR. For today's VR implementations, the attention lies especially to the visual perception, although other studies included vibrotactile and auditive feedback simulation (Zhao et al., 2018). Therefore, an overview of the sensory perception within a VR application is given in the following chapter. However, this work focuses on comparing the visual perception within VEs, which leads to a more detailed description compared to the other primary stimulated senses in VR.

## 2.2 Sensory perception in virtual reality

The literature often reports creating a "perfect VR" eliciting sensory inputs, which people perceive in the same way as in real conditions (Cuervo et al., 2018; Dörner et al., 2019; LaValle, 2019). In the last decade, the VE visualization enabled by HMD (more described in the next chapter) plays an increasing role due to the possibility of generating multisensory inputs. Those are mainly generated by presenting visual, auditive, and haptic stimuli appearing during interaction in VEs (Fröhlich & Wachsmuth, 2013). Newer findings also reveal possible thermal biofeedback ensured through heat conduction of flowing liquids with different temperatures (Günther et al., 2020). Many applications stimulate only a few senses, and are therefore characterized in different levels of immersion such as non-immersive (Desktop VR), semiimmersive (Fish tank VR) and immersive VR systems (Mandal, 2013). Since the aforementioned senses predominate the VR experiences, general information of their provision is described in the following chapters. Since the included studies of the current work pay special attention to the visual perception, this topic is explained in more detail compared to the others.

### 2.2.1 Visual system

To visually perceive the surrounding allows us to provide accurate information about the characteristics of the world. Visual perception refers to the reception and processing of optical stimuli and accommodates many systems going far beyond the mere taking in of information. One of these systems is the visual system (VS) consists of the eyes, optic nerve, parts of the thalamus and the brainstem, and visual cortex. Generally, transducers (receptors) convert the light-energy stimulus into an electrical signal (neuronal impulse). Those signals are transmitted to deeper brain regions and pass through different interactive systems. In sports, the VS is used especially for spatial orientation, detection of movements of teammates, opponents and game objects, anticipation of movements and control of own and other people's movements (Witte, 2018). Approximately, the sensory input forwarded to the brain consists of 80 percent of the visual system and systems that process visual information (Clark et al., 2020). To perform a numerous of motoric tasks, the visual processing, visual fields, and visual reaction times are essential for supporting sport performances and preventing injuries.

The VS supports our acting and performing in a tremendous way by steering the individuum through the surrounding and guiding the limbs in the execution of the activities (Land, 2009). This was examined by simply task demands in which participants were asked to draw repeatedly lines with both hands, once with open and once with closed eyes (Elliott et al., 2001). They clarified that movements are still executable when they are programmed and guided by the first impulse of sensory perception when the eyes were closed (open-loop) or using the visual feedback for movement's improvement (current control). Land (2009) described different systems which are involved in vision guided movements (see Figure 4). This graphic mirrors the importance of the correlation between the visual perception and movement initiation, and interaction with objects, which is the case for many sports. If future implementations in VR are planned, it should be ensured that the visual input supports our actions or movements equally in both conditions. To realize this, higher cognitive processes including different systems are required, and separated tasks were assigned to them.

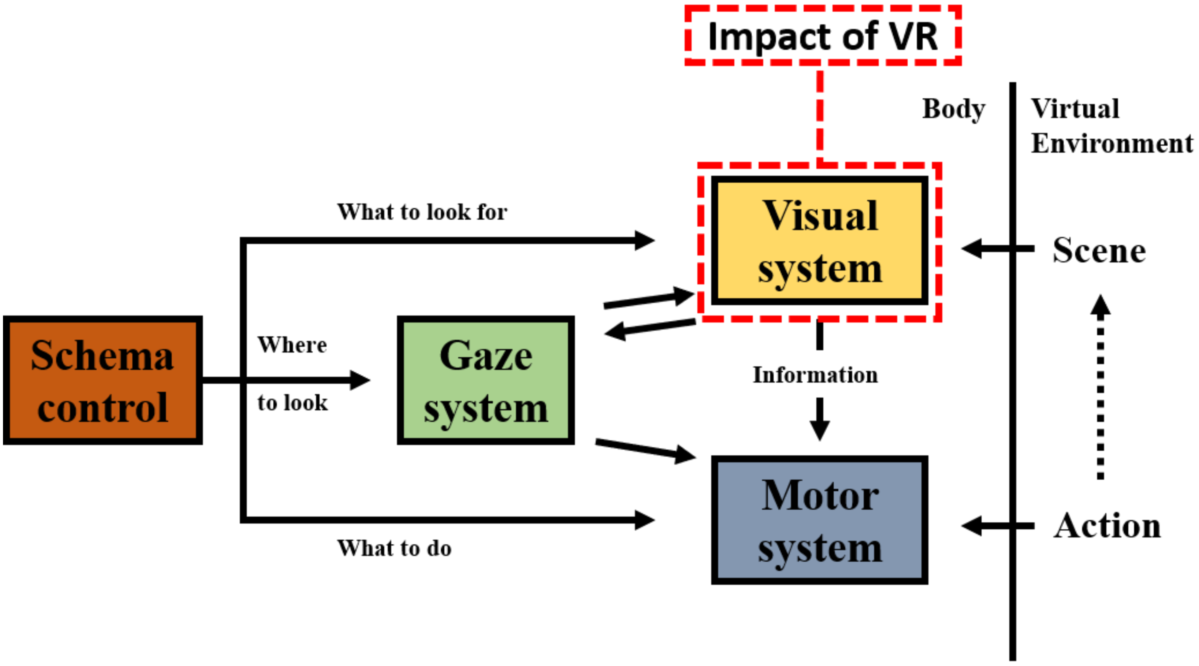


**Figure 4** Correlation between the schema, gaze, visual, and motor system inspired by Land (2009, p. 52, Figure 1a). The impact of Virtual Reality (VR) is predominantly on the visual system identifying the virtual target. Often, the user's body is not visualized in VR, which means that movements cannot be corrected by visual information processing.

The primary role of the gaze system (GS) is to initiate eye-movements (usually of the head and trunk as well), bringing the image of the desired target onto the fovea centralis. Memory plays an essential role since targets are often located out of sight, which positions have been retrieved from it. This system contains major steps, first to initiate body movements and second to move the eyes being able to fixate the target (often achieved by two saccades). The motor system's (MS) role is to control movements, including all subsystems, which can be generated through a vast repertoire of learned actions since those movements differ within their complexity (Land, 2009). The VS coordinates between the GS and MS by identifying the target and providing appropriate directional guidance to the MS in its orientation or physical properties (Land, 2009). The VS also relies on the distance and depth indicators to determine the surrounded objects in a virtual scene (Ghinea et al., 2018). In addition, the author describes a schema-system that has overall control of the others and disposes of an internal representation of each task (Norman & Shallice, 1986). The correlation between vision and action is highly demanded research field. Generally, two pathways during visual processing exist helping us to encode crucial information. The ventral pathway (projecting from primary visual cortex to the inferior temporal lobe) allows the perception and identification of visual inputs, and the dorsal pathway (also projecting from the primary visual cortex to posterior parietal lobe) supporting visual information (reafference) for guiding real-time actions. The impact of VR on VS is raised controversial what will be discussed later in this work.

Understanding how the visual perception works within VR can improve the quality and quantity of information being displayed. To examine whether people visually analyzes images to the same extent in VR to RW, various mechanisms have to be considered, such as Visual Attention (VA) or Visual Memory (VM) (Healey & Enns, 2012). VA denotes the mechanism to select regions for more detailed observation what is a critical role for what we see. With this, the attention can be driven by different objects' forms, colors, layout, which leads to focus on specific items popping out of the display (Healey & Enns, 2012). The authors state that benefits for search strategies resulting from memory seem to occur unconsciously and dependent on the task context. The number of image views and an increased observation time might increase incidental spatial knowledge of the scene (Healey & Enns, 2012).

The visual perception is enabled by different abilities, which also crucial within sports. According to this, it is essential to see the fixed point sharply to collect detailed information that could later be important for the movement initiation. This is realizable through the convergence (alignment to the visual axes of both eyes to the fixed object) and accommodation (adjusting the lens via the ciliary muscles) (Witte, 2018), which are also used to identify distances. To generate sharp vision on objects that are moving, pursuit eye movements are necessary to maintain information processing. However, for detailed observation, the objects should not exceed 10°/s since they are not sharply perceivable. Herby, the human needs to initiate saccades, defined as rapid and jerky eye movements. In this context, In addition, eye movements play a major role in self-motion to fixate the target to be reached, to use additional visual feedback on certain disturbance variables, and to compensate for head movements (Witte, 2018). Another property of the eye should be considered by the creation of an artificial created world that should be perceived as real from the user. The human eye has a spatial and temporal resolution, which is of course of special importance in an artificially created world like in VR. Although the athletes are forced to move the eyes, extracting valuable information from specific scene components, they can also use peripheral vision (PV) during execution and planning movements. Previous findings reveal advantages of PV within sports to monitor external cues (e.g., game objects, players, teammates), recognize motion changes (feints, attacking limbs) and process relative-cue positions (e.g., relation between opponent's body parts) (Vater et al., 2020).

### 2.2.2 Auditive system

Humans perceive airflows generating mechanical waves, converted into vibrations of the eardrum in the middle ear. Afterward, the cochlea converts the mechanical energy into electrical signals transmitted to the brain via the auditory nerve. The information of the amplitudes and transit time differences of both ears provide spatial information possible for more than just one auditive source, as long as the positions differ significantly. In VR, additional output devices can also be used to convey auditory signals to the user. These should have realistic effects since they are often used for orientation as well. Such an audio system is crucial for the temporal assignment of events resulting in the VE (Dörner et al., 2019). At the current time, sound planning is not often included, but studies examined the role of noise within VEs for designing urban process, but still, the visual design strongly outperform the others (Echevarria Sanchez et al., 2017). This can be confirmed through other studies, which examined that audio dimensionality has a more implicit influence on player experience since VE's entire sensory experience is essential (Rogers et al., 2018). However, the authors also report that basic feedback sounds increase a successful VR experience.

#### 2.2.3 Haptic system

Haptic describes the sensory and motor activity that involves sensing object properties (size, contours, surface texture, weight) by integrating the sensory impressions felt in the skin, muscles, joints and tendons (Dörner et al., 2019). The haptic feedback is provided by different input devices such as a mouse, gloves, keyboards for desktop VR applications, motion controller for increased immersive VR systems or force-feedback robots (van Polanen et al., 2019). Those input devices are combined with output devices since the haptic output is usually elicited through the users' movement. The combination with motion capturing systems that enable real-time positioning tracking for any desirable object and its related virtual mesh can generate haptic feedback in a rather circuitous way. A more straightforward method is working with colliders and rigid body function within the game engines, which can receive forces and torque to make objects move realistically and detect collisions initiating modifications of the VR simulation.

### 2.3 Benefits of head-mounted display virtual reality

The merging of research mirrors a high number of benefits conducting experiments or working with VR. Besides, VR applications offer the possibility to explore large VE in a smaller physical space (Hirt et al., 2018), which enables the conduction of any imaginable scenario. Nowadays, VR Systems provide affordable costs and high accessibility in most domestic environments (Düking et al., 2018). Different devices were used to visualize VEs, such as VR desktop, Cave Automatic Virtual Environment (CAVE) (Cruz-Neira et al., 1992), and head-mounted displays (HMDs).

In recent years, the HMD became more attractive for scientific use (Kwon, 2019; Zhang, 2017) and is the most common type of VR consumer (Won et al., 2017). It serves as an output device to visualize the computer-generated three-dimensional virtual environment and deliver sensory information (Maples-Keller et al., 2017). Different kinds of HMDs, such as Oculus Rift[4] and HTC Vive (and HTC Pro Eye)[5] etc., closely match the perfect illusion of VEs (Cuervo, 2017). With an integrating gyroscope, the user's head position is trackable in real-time and the adapted FoV is computed and presented on display. In general, VR technologies allow direct interaction with objects located in the VE. Those interactions are crucial for the feeling of being present within VEs (Berg & Vance, 2017). Previous studies show that HMD-based intuitive systems ensure better user experience, an increased feeling of being present (Mondellini et al., 2018), and awake higher immersions (Tan et al., 2020; Zhang, 2017). To ensure higher immersion, a minimum of refresh rates (15-20 Hz) in display performance is recommended (Brill, 2009), which is the case for at least newer developed HMDs. Due to the lightweight and reduced size compared to previously developed output devices, the portability is given and, therefore, the number of application areas increase (Zhang, 2017). The HMD can also stimulate other sensory impressions such as auditive (integrated head-phones), but manipulating the visual input predominates, which is generally the case for human's ability to receive environmental information (Sinnett et al., 2007). To achieve the same degree as it occurs in real conditions, the HMD must match human visual perception limits realized through adequate display resolution, FoV, and frame refresh rates (Cuervo et al., 2018). Additionally, it provides opportunities to measure gaze behavior or use it in terms of gaze-controlled interactions (Meena et al., 2018), realizable through integrated ET-systems, which do not drive up the weight in an unacceptable framework (Clay et al., 2019). Due to the ongoing technological development, the display resolution and target refresh rates increased (Patney et al., 2016), leading to higher immersion, feeling of being present, and enabling a more detailed presentation of the VEs.

Related to memory skills, a previous study examined the experience of a simulation on an HMD, which was equated with actively perception of the visual world (Hine & Tasaki, 2019). They distinguished between active and passive viewing and reported that previous findings found positive effects to spatial memory when the participants observe the scene by actively viewing, meaning the HMD shows the angle of view depending on the user's head direction. The authors claimed about controversial research concerning memory performances of active or passive viewing (Hine & Tasaki, 2019). This study examined the active or passive perception

[4] https://www.oculus.com/en-us/rift/. Oculus rift, Mar. 2016
[5] https://www.vive.com/de/product/vive-pro-eye/overview/

of a 3D movie in HMD, which results could not transfer to the visual observation of a three-dimensional virtual room. The participants reported 3D perception even though there was no binocular disparity. Furthermore, the active viewing inhibited the memory performance and further examinations are needed.

Previous findings could already demonstrate that those technics are applicable and suitable for different aging groups or for people with impaired health. They revealed the potential to increase motivation for children (Harris & Reid, 2005) and enhance learning acquisition (Sattar et al., 2019). This technology is also applied to older adults with cognitive and physical impairments with no negative side-effects (Appel et al., 2019) or to children who have autism spectrum disorder (Malihi et al., 2020). Furthermore, this promising tool allows the control or manipulation of events in a way not realizable in a real-world setting (Harris et al., 2019). Another study compared the HMD to stereoscopic widescreen displays (SWDs), whereas the HMD performed worse concerning superimposed real and virtual objects, distortion, egocentric distance estimation, and weight (Lin et al., 2019). Despite the many advantages, the authors point out specific guidelines for designing of immersive VEs (mainly considered on VR gameplay), such as avoiding unnecessary audio types and perceptual mismatch stemming from vertical navigation. They also recommend limited play-session time and endorse moments of reflection and visual appreciation of the VE improving VR experiences (Rogers et al., 2018).

### 2.4 The usage of virtual reality in sports

Technical support during the evaluation or improvement of athletics performances is no longer indispensable (Ahir et al., 2020; Chen et al., 2018; Fleming et al., 2010). Studies showed that VR amplifies the user satisfaction in terms of vividness, interactivity and telepresence compared to traditional media especially for people who are interested in the sport to be learned (Kim & Ko, 2019). A survey shows that after being confronted with possible VR-training scenarios, the majority declared themselves being ready to use it (Gradl et al., 2016). In addition, this innovative technology is not only usable for improving sports performances of young and healthy users, but also for physically and mentally limited people (Kang & Kang, 2019). Previous created overviews show that VR has been integrated into different kinds of sports using the previously listed benefits (for review see Neumann et al., 2018). Further suggestions were made how to use VR to enhance the understanding of performance in team ball sports (Faure et al., 2020). Especially in the last decade, the number of the study's examining the suitability of VR technology concerning examining, learning, or training motoric and perceptual skills has increased (Mohanty et al., 2021) and expanded to many different sports fields.

Since various skills and abilities are required to successfully perform sports-specific movements, a few examples are presented to reflect the current application possibilities of VR in sports. Petri et al. (2019) showed that VR training leads to an improvement of the athletes' response behavior on a virtual avatar's attacks. They emphasized that VR training should be used in addition to conventional training and listed advantages such as the safety within VEs due to no physical impact or the deployment of different training methods, e.g., other virtual avatars executing faster attacks (Petri et al., 2019). Another study's purpose was to create a system including a VR model to enable teaching and tactical training in basketball, including visual and auditory feedback getting more sports experiences associated with real conditions (Huang et al., 2019). Bird (2020) could show that VR is suitable to train perceptual-cognitive skills which is in line with other studies (Miles et al., 2012), relaxation strategies and injury rehabilitation using head-mounted display virtual reality. The author points out that further investigations of the effectiveness of sport psychology interventions are necessary to recommend the usage of HMDs to the full extent (Bird, 2020). Ulas and Semin (2020) examine biological and motivational effects between VR and conventional exercise. They report greater motivational effects in VR, whereas in traditional training, greater physical improvements were obtained (Ulas & Semin, 2020). Other positive aspects such as an increased heart rate leading to an increased kilocalorie consumption or distracting factors from exercise have also been reported (McClure & Schofield, 2020).

It is one thing to acquire in VR but calling them up under natural conditions is another. Therefore, further studies examine possible transferring effects of in VR-adapted skills into real-life for table tennis (Michalski et al., 2019), for baseball batting skills (Gray, 2017), or for darts (Tirp et al., 2015). Michalski et al. (2019) discussed that transferring skills needed to be considered for other skill levels and training environments. In Tirp et al. (2015), the VR training group increased their throwing accuracy and the quiet eye duration being significantly larger after intervention, however, the real training group exceeded all other training groups in terms of throwing accuracy. Interestingly, the results of Gray et al. (2017) show significantly higher improvements for the VR training group in terms of batting performance over time compared to the others, even for the one training under RW conditions, which is line with other findings (Bardy, 2011; Bergamasco et al., 2017). Maintained improvement of performances after one month test repetition was also verified concerning baseball patting (Gray, 2017). All studies included the usage of HMDs, whereas studies including other VR display options such as

CAVE or VR-desktop often reveal negative effects on the response behavior to simulated target distances in rugby ball passing skills (Miles et al., 2014), which makes it hard to transfer the effects of training to studies worked with other VR application tools.

VR also offers many advantages that cannot be transferred to RW conditions. Therefore, a further study examined not only the comparison between real and virtual training of basketball free-throw performances, but the authors also tested whether the possibility of generating additionally visual feedback of the ideal ball trajectory during VR leads to significant improvements (Covaci et al., 2015). In addition, the impact of different perspectives such as first-person (1PP), third-person (3PP), and third person with visual guidance (3PP + guidance) on the performances in VR was examined. Therefore, they compared the performance variables of the beginners which participated in intervention to the experts' performances. An underestimation of distance was observed in the VR, however, this could be compensated through displayed visual guidance feedback (ellipses as ball trajectories). Surprisingly, they also found a higher height in releasing the ball in VR (3PP + guidance) compared to RW, which is an indicator for better throwing technique (Covaci et al., 2015). This investigation's main conclusion was that VR training could be close to training effectiveness under real conditions if visual guidance is provided in the third-person view. However, the first and third-person perspective in VR was less effective than RW, which should be not disregarded, since the most VR scenarios use first-person perspectives during VR experiences to generate natural conditions. Real-time feedback is an essential factor that makes VR usage in sports more attractive. Hülsmann et al. (2018) examined how verbal information and automatically generated visual augmentations (color highlights on the participant's avatar) can be used from the participants to acquire satisfactory the technical demands. Their developed system can classify movement errors and generate real-time visual feedback better than recent neural network-based approaches. However, it still has its limitations in temporal warping, feature selection, or the variety of errors within complex movements itself (Hülsmann et al., 2018).

Due to a large number of applications, more and more benefits are crystallizing. Yang (2018) mentioned the advantages of working with VR in sports, such as safety, feedback, and motivation. The author also mentioned the VR sports simulation system refers to the human modeling technology including physical (shape, structure) and physiological (function index, blood pressure, vital capacity index) characteristics, data acquisition technology realizing data of real human motion, scene design technology providing powerful animation settings, rendering, light setting, etc., and system interaction technology enabling real-time feedback (Yang, 2018). Realizable applications in college physical training based on football, aerobics, and swimming training are given, and VR technology can be included in college physical education.

Although VR is already used in learning or practicing motoric skills, different results show inconstant outcomes concerning the quality of skill acquisition compared to real training conditions. In addition, preliminary study designs such as missing interventions for all training groups (in RW, in VR, control group) make it hard to compare each skill acquisition's quality in terms of efficiency and effectiveness. Furthermore, the attained skill improvements seemed to occur only in VR since no relations in realistic situations were made. Moreover, working with a small sample size leading to less statistical power, no conclusion on the effectiveness of the population can be drawn. The different outcomes of the previous interventions concerning the training of motoric skills may lay in other technology or the users' perceptual abilities, which are also influenced by the previously collected experiences in VR immersions. In the next chapter, the factors which may elicit those differences are presented, and solutions to reduce their consequences are provided.

## 2.5 Reasons of emerging differences between the real and virtual environment

Although the current VR devices enable realistic-looking VEs and various interactions, surprising phenomena are observable in user's behavior during VR experiences. Currently, authors claimed that HMDs provide visual cues, but those differ from the RW (Harris et al., 2019). Dörner et al. (2019) listed possible reasons and provided solutions for generating VR experiences without interruptions or the occurrence of cybersickness-associated symptoms. The authors enumerate different factors as the leading causes: deviating observation parameters, dual images, Frame Cancellation, Vergence-accommodation-conflict (VAC), discrepancies in the spatial and movement perception, Cybersickness, and issues of the vertical parallax (Dörner et al., 2019). In the current work, similar factors are taken up and divided into two fields. Some of them explain differences due to technical limitations, and others are caused through differences within human behavior.

### 2.5.1 Limitations elicited through restricted virtual reality technology

For creating a VE, a virtual camera is used to elicit a picture observed by the user. During scene observation, light rays are reflected from the objects to the human eyes and produce further impressions. Hereby, previous findings showed that currently used hardware components can not realize real-world lightness within VEs to the full extent affecting the user's visual acuity (Luidolt et al., 2020; Patney et al., 2016). In addition, the structural difference between the planar lens of the virtual camera and the curved one of the eye's retina causes different aperture angles may occur, resulting in different FoVs between the user and the virtual camera (Dörner et al., 2019; Steinicke et al., 2009; Steinicke et al., 2011). This has consequences regarding the impressions of enlargements, reductions, distortions (Steinicke et al., 2009), distance estimations (Knapp & Loomis, 2003), and the inclination of objects within virtual scenes. The visual system corrects the distortions to a certain degree (Vishwanath et al., 2005). However, it should be minimalized as much as possible, especially in a VR scenario enabling interactions implies active movement. The current HMDs provide a small deviation of observation compared to other VR devices. Concerning the restricted FoV, another phenomenon called Frame Cancellation may occur, which reduces the illusion the perceived object lays in front of the display to awake a three-dimensional impression of the virtualized scene (Mendiburu, 2010). The edge of the display obscures the object appearing in the FoV, so the effect of disparity is ineffective, and the loss of depth perception is the consequence (Dörner et al., 2019). In addition, the problem of Virtual Eye Separation occurs, meaning the distance between the two cameras projecting the picture separately to each eye differs from the pupil distance. Most of the HMDs allow adjusting the IPD individually. Although the user will not recognize incompatible settings, it can lead to nausea. Previous findings also show that eye height and IPD manipulations can affect the perception of scale within realistic VEs (Kim & Interrante, 2017).

In the HMD, stereoscopic vision is prevented by bringing different two-dimensional images from two slightly different viewing angles into the right and left eye. When the user cannot fusion the two presented images, diplopia appears, which means that two pictures are perceived separately by each eye, resulting in a less feeling of being present within the VE. A reason, therefore, is the remaining distance between the display and the human eyes since the accommodation is always limited to the display level, which is also an issue of VAC. Therefore, the virtual objects can only be presented within a restricted domain (parallaxbudget) within the stereo display. The comfortable domain that enables the fusion of the two different images effortless is called the Pericival's Zone of Comfort (Hoffman et al., 2008). Despite the tremendous progress of VR display technology development, minimizing visual discomfort realizable by rendering correct focus cues remains an unresolved challenge (Hua, 2017).

Many studies examined the physiological perceptual processes in VR and pointed out differences compared to real conditions. Concerning the visual system, studies also reported less resolution in HMDs (approximately 2800 x 1600 pixels) compared to the human eyes (32000 x 24000 pixels) (Roth et al., 2017), limiting the sharpness of detailed information within the VE. In addition, unsatisfying differences in shadowing and color appearance have been found in VR, which harm the estimation of room sizes (Billger et al., 2004). Furthermore, distances are often underestimated, which could be improved by exploring the VE by walking interaction (Kelly et al., 2018). Other factors can also limit the experiences made within VR. A big challenge is generating haptic feedback that helps us understand physical properties such as shape, texture, temperature, etc. (Zenner & Kruger, 2017). Multisensory feedback is beneficial to perceive realistic impressions leading to higher immersion and, therefore, more minor differences within participants' performances are expected. Regarding the different sensory inputs, another study shows the importance of vision for proprioception, and declines that this may be disrupted by the use of immersive VR (Valori et al., 2020).

### 2.5.2 Limitations observable through human behavior

One-fifth of the population suffers from stereoblindness (Dörner et al., 2019), in which information from disparity cannot be evaluated. As a result of this, other cues extracted by the near and far-accommodation (Leschnik, 2020), monocular depth-perception such as masking (Rock, 1985), magnitudes of objects, and image blur (Dörner et al., 2019) can be used to further collect crucial information for identifying depths within the visual field.

Due to the aforementioned factors that could tremendously harm VR experiences, it should be clarified whether tasks requiring different abilities and skills are similar to RW conditions. Controversy results of persisting studies and missing examination of in VR obtained skills and the resulting transfer to real condition leads to further analyses, which could finally erase any doubt concerning VR usage in general and sport-specific purposes. In addition, the comparison of participant's sport-related performances between RW and VR has rarely been made, making it hard to recommend VR for all fields of application. Furthermore, it is crucial to examine whether the used display technology is suitable to complete the demanded tasks since the choice between different devices depending on the application has not yet been answered sufficiently (Lin et al., 2019).

Cybersickness (CS) is defined as a constellation of symptoms of discomfort and malaise elicited by VR exposure (Stanney et al., 1997). It is a form of visually induced motion sickness, which occurs through the mismatches between observed and expected sensory signals, self-motion, visual display characteristics, and gameplay experiences (see Weech et al., 2019). CS arises from vection in which movements are performed in VE, but these deviate from those from RW, where the person is sometimes stationary (Davis et al., 2015). The measurement of CS is made through objectives, such as respiration rate (Dennison et al., 2016), heart rate (Nalivaiko et al., 2015) and skin conductance at the forehead (Gavgani et al., 2017), or subjective measurement, particular multi-item questionnaires such as the Simulator Sickness Questionnaire (SSQ) including sixteen items categorized in three subscales of oculomotor discomfort, disorientation, and nausea (Weech et al., 2019). It has emerged that different factors can impact the task performances of participants, such as the lack of presence in VR, less individual motivation, and insufficient experimental instructions. In addition, previous findings show the inverse correlation between CS and the participants' performances and also reveal the impact of CS on the feeling of being present (Cooper et al., 2018; Kim et al., 2005).

# Chapter 3

## Objectives and Research deficits

In recent years, many different research fields have been found to approach various VR applications' deficits or to investigate human behavior within the VE. VR has great potential to enhance sports training and support the learning process extensively regarding the benefits listed before. The problem arises when comparing performance in VR to that from RW since differences are often noted. This could be caused by a purely artificially computer-generated world that cannot fully keep up with the RW. Since the visual perception is the dominant sense stimulated within VR systems, a more detailed analysis of the comparison between VR and RW of all related components (2.2.1) could reveal possible differences, further used to improve future implementations. To better isolate the issues that arise with VR differences to the RW should be examined to test the suitability of today's VR systems. Before recommending VR for its integration into sports without hesitation, at least basic skills such as accurate walking, precise viewing of visual stimuli, similar distance estimations, etc., should be performed without much deviation to RW. Otherwise, VR could even lead to disadvantageous results in terms of RW movement execution and could further harm the acquisition of sports-specific skills.

Although VR is already used in specific directions and its benefits are indisputable, less research has been done concerning the suitability for sport-related purposes. Often, VR is used without having evaluated it sufficiently beforehand. To be more specific, there are no clear guidelines for which sports the current VR devices are suitable and whether the transfer of skills learned in VR can be transferred to the full extent to RW. Of course, one should not disregard the continuously advancing technical progress and closer approximation to real conditions. Efforts are being made to bring more and more user-friendly products to the market, primarily characterized by high graphic resolution and realistic appearance. A closer examination of the visual perception in the current VR devices can also reveal the current state of the devices by revealing the properties for adequate user interaction.

Therefore, the current work's goal is the investigation of the visual perception in VR compared to RW. In addition, the suitability of VR concerning the usage in sports will be discussed. To verify this, the work focuses on analyzing fundamental skills or abilities that are prerequisites for sports. For example, previous findings emphasized the requirements for precision aiming tasks are accurate distance perception and natural interactions within VEs, both crucial factors to complete sport-related movements (Covaci et al., 2015). The basic skills and prerequisites covered in this work are composed of gaze behavior, spatial orientation, and the visualization of the body. If the basic skills are not comparable to those from RW, it makes it hard to argue why the currently used VR tools are suitable to perform adequate training or leading to a successful transfer instead of leading to the opposite of desired effects. An advantage of VR can be exploited, as body regions can be removed from vision without any effort, which could reveal insight into how much of the own body must be visually perceivable to complete sport motoric tasks.

To examine VR-suitability, the participants' performances from simple to advanced motoric tasks are compared between both environmental conditions (RW and VR). This chapter describes each study's purpose and the current state of research. Besides, it offers a proposal regarding the involvement of VR in sports. The studies form the basis of this work, and the concepts are elaborated with special consideration on the visual perception. Basically, three main sections are worked on (see Figure 5), and all of them pursued testing VR for its application in the sports field.

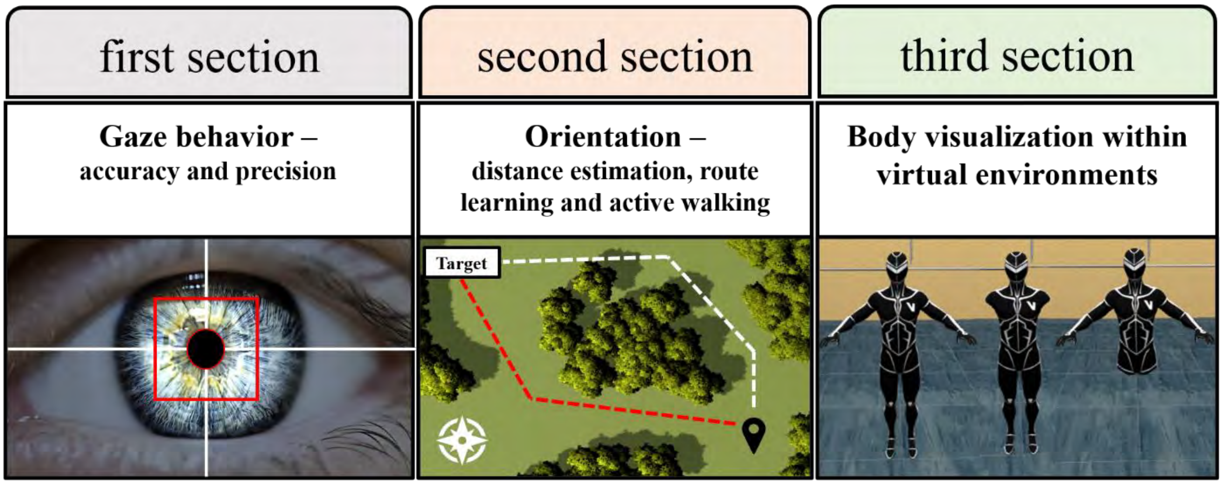


**Figure 5** Overview of the main sections treated in this work.

### 3.1 Gaze behavior – accuracy and precision

Vision training is crucial to enhance sports performances and prevent injury (Clark et al., 2020). Multiple pathways in the central nervous system determine where and what the eyes see (Blumenfeld, 2018). To examine this in more detail, analyses of the visual perception have increasingly been conducted in sports science lately (Bandow & Witte, 2021). The visual perception analyses can be done indirectly by observing participants' behavior or directly with the opportunity to use measurement systems such as Eye-Tracking (ET). Currently, ET is now includable within HMDs (Clay et al., 2019), which leads to further ideas regarding the application areas and the improvement of usability (Sun et al., 2018). During sports, to visually perceive opportunities for action, the athletes need to conduct movements of their eyes, head, and body to fully explore their surrounding field (McGuckian et al., 2018). The eyes need to be permanently moved to enable sharp vision (fovea centralis) of the fixated stimuli. Since it is intended to use VR for sports, it is fundamental to examine whether those can be fixated to the same extent as in RW. Therefore, the first section focused on analyzing eye movements related to the gaze accuracy and precision during the perception of static and dynamic stimuli. In addition, a comparison between the gaze parameters captured in the real and virtual scene was made to examine whether visual stimuli can be fixated to the same extent in both conditions.

Before presenting the status of research and the resulting deficit, a description of ET systems and the outcome parameters is given to ensure basic comprehension. ET offers the opportunity to collect objective measurements of visual behavior (King et al., 2019). It enables to record gaze parameters during conjunctive movements[6] such as fixations, saccades, smooth pursuit movements, micro-movements, as well as during disjunctive movements[7] such as vergence movements (Essig, 2007). For the classification and calculation of those gaze parameters, the gaze accuracy and precision determined by the raw data (point of regard or point of gaze[8]) extracted from the ET-systems are the fundamental sources. Therefore, it is crucial to examine whether the gaze data quality differs between the conditions since existing differences make it hard to compare gaze behavior within VEs to real-life situations. In RW, many studies exist in which gaze accuracy and precision had been measured (Dalrymple et al., 2018; Holmqvist et al., 2011), whereas in VR, no investigation was made evaluating both parameters for HMD integrated ET systems.

The human visual system is limited to 1-2° sharp vision within the FoV, leading to constant eye movements during scene observation (Vater et al., 2017). With Et systems, it is possible to track participants' gaze and refollow the visual attention concerning the limited sharpness of the FoV. The ET data's quality contained four components (Dalrymple et al., 2018): spatial accuracy, spatial precision, temporal accuracy and, robustness. In the current study, spatial accuracy and precision are considered between the comparisons of RW and VR.

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[6] Both eyes move in parallel during the inspection of static or dynamic objects (Essig, 2007, p.62).
[7] Both eyes move in different directions changing the angle between both eyes (Essig, 2007, p.62).
[8] The term point of regard (POR) will be used in the further course of this work to avoid ambiguities.

### 3.1.1 Accuracy

Accuracy is described as the averaged deviation between the position of the gaze point captured by the ET system and the position of the considered point (target stimulus) (Holmqvist et al., 2011). It is stated through the visual angle within the FoV (Krokos et al., 2019) and reveals occurred differences in attention and visual information processing between individuals (Pastel, Chen, Martin et al., 2020). The manufacturers of today's ET devices specify a deviation of under 0.5° in their systems (Feit et al., 2017), whereas higher accuracies occur when the observed target is located at the center in front of the ET system due to the largest size of pupils helping for their detection (Hornof & Halverson, 2002). Gaze accuracy can be affected by the homogeneity of participants, using different calibration methods, the characteristics of the human eye, operators experiences, contact lenses, downward-pointing eye-lashes, smaller pupil size, different systems as well as environments, and different calculation methods (algorithms) to determine gaze parameters (Blignaut & Wium, 2014; Feit et al., 2017; Hooge et al., 2019; Nyström et al., 2013).

### 3.1.2 Precision

For the determination of the event detection, the precision of the used measurement system should be considered. The precision represents the distance between repeated samples of the PORs' location when the true POR is assumed to be stable (Dalrymple et al., 2018), which is observable during tasks requiring stimulus fixation without the initiation of saccadic eye movements. Lower deviations (measured in °) of the repeated samples indicate a more precise ET system. In the past, different precision values were found within different ET systems such as tower-mounted (0.01°-0.05°) or remote ones (0.03°-1.03°) (Nyström et al., 2013). Less precise systems affect the output of gaze parameters such as shorter (Wass et al., 2014) or longer fixation durations (Hessels et al., 2017).

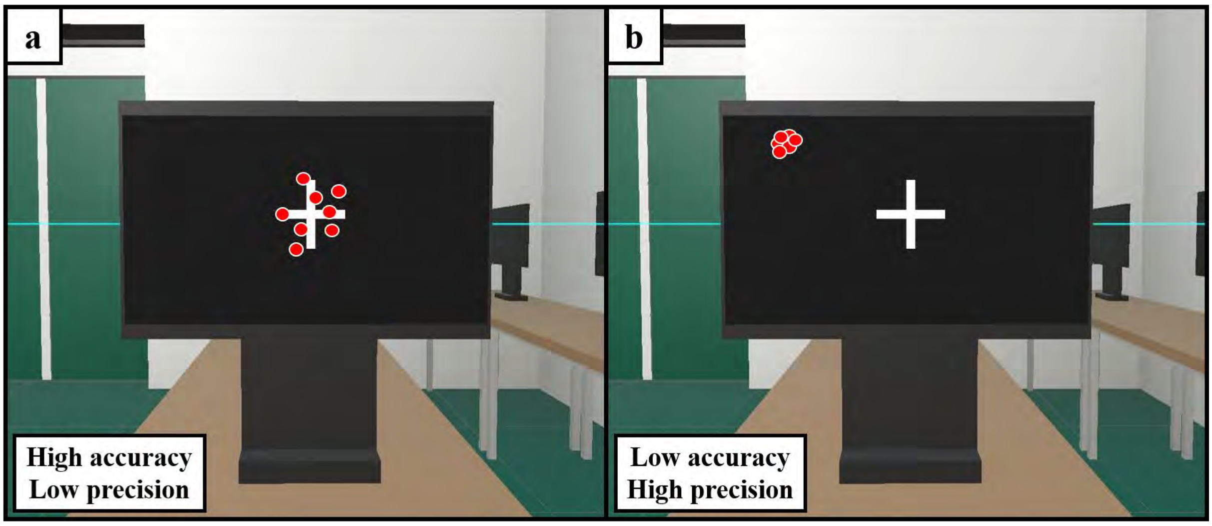


**Figure 6** Example for high and low accuracy and precision. The white cross at the center of the screen indicates the stimulus that the participants should fixate. The red dots indicate the point of regards (POR) captured by the eye-tracking system. In a), high accuracy and low precision values are detectable since the target stimulus (white cross) was fixated accurately. In b), the target stimulus is less accurately fixated, but the system measures the PORs precisely over time.

The analysis of the accuracy and precision of the gaze tracker inside a virtual 3D space has been further extended to effectively utilize gaze data for user interactions (Kangas et al., 2020). Both parameters play an immense role in developing higher implementations in VR. For example, saccadic eye movements were used to facilitate infinite walking in VEs, although the physical surrounding is limited in space (Sun et al., 2018). In addition, tracking visual acuity enables to increase rendering performances without requiring higher computational capacity (Meng et al., 2020; Patney et al., 2016; Roth et al., 2017; Weier et al., 2018). Hereby, the authors stated that high quality of gaze accuracy and precision are a prerequisite to guarantee a smooth way for foveated rendering (Roth et al., 2017; Weier et al., 2018). Gaze accuracy and precision of the ET need to be determined because they could trigger differences within the visual perception. Those differences could appear through the algorithms used for event detection that rely on data quality. For both interaction and measurement of the visual perception in VR, this is of great importance.

### 3.2 Spatial Orientation within virtual reality

Spatial orientation contains a set of skills or sensory-motor control systems (including sensory input from vision, proprioception, and the vestibular system), allowing us to determine one's position related to the environment (Carbonell-Carrera & Saorin, 2018; Notarnicola et al., 2014). This ability is crucial for daily movements and tasks (Pastel, Chen, Bürger et al., 2020), especially wayfinding or homing in tasks (Cao et al., 2019; Ishikawa, 2019). Many different approaches exist in terms of describing spatial orientation. Among others, it is described as a visual-spatial skill that enables us to build up a cognitive map of our surroundings, being aware of self-location and target position (Wolbers & Hegarty, 2010).

Currently, there is a high need for how to assist people for better orientation in daily life. Therefore, the primary analysis of previously conducted experiments dealt with spatial navigation skills within wayfinding tasks, which involves learning a route (Wiener et al., 2020) and recreating it from memory (Cao et al., 2019) or finding the way between places in the environment (Bruder et al., 2012; Diersch & Wolbers, 2019). The authors emphasized that judgments about spatial information between fixed or dynamic cues within the surrounded environment are essential to make further statements of one's ability to orientate. This ability involves basic perceptual and memory-related processes, in which information needs to be adjusted over space and time (Wolbers & Hegarty, 2010). In this context, the term spatial memory is used, which is known as a cognitive process that makes it possible to determine and recognize the position of objects and their relations to the environment (Kozhevnikov & Hegarty, 2001). Besides the extrinsic structures, the intrinsic ones like the self-imagined arrangement of axes, columns, or rows within the surrounding play an equivalent role (Kelly & McNamara, 2008). Furthermore, the ability to estimated distances from egocentric or allocentric perspectives specifies the orientation in places. Whereas egocentric reference systems are known to extract location and orientation relative to the observer's position (Wolbers & Wiener, 2014) and seemed to play the dominant role specifying objects' locations (Battaglia-Mayer et al., 2003), the allocentric information can be used independently from one's position and is specially used for memory-guided reaching in depth (Klinghammer et al., 2016). Both systems work simultaneously, and the completion of our daily life activities and primarily during sports, depend on them (Pastel, Chen, Bürger et al., 2020).

To measure or train spatial orientation skills, VR has been described as an advantage tool due to its greater degree of control (van der Ham et al., 2015), the usage in conjunction with neuroimaging techniques (Sutton et al., 2010), and the safety during the high level of interactions or general performing activities (Jha et al., 2020). Those advantages are only relevant if the processes of navigation (or other essential skills needed for orientation) are similar enough to those from RW (Kimura et al., 2017), otherwise, no transfer of adapted skills can be ensured. In this regard, the locomotion technique realized through VR applications is an additional factor that contributes to spatial orientation. Physical rotations and translations are the basic constituents of navigation skills (Riecke et al., 2010). Many studies have already proven that physical motion performs better and causes fewer problems than the alternatives such as joystick controlling or teleportation techniques (Ruddle et al., 1999; Sayyad et al., 2020;

Simeone et al., 2020). Previous research provides an overview of existing challenges in enabling unconstrained walking in VR larger than the tracked physical space and providing the user with appropriate multisensory stimuli related to their interactions (Nilsson et al., 2018). Despite the remaining challenges, VR is already used as a valuable tool for improving spatial orientation by exploring VEs for children with physical disabilities (Stanton et al., 1998) or those who suffer from topographical agnosia (Kober et al., 2013). Therefore, spatial orientation skills were often tested by letting the participants perceive and then interact within VEs (Kimura et al., 2017; Milleville-Pennel et al., 2020).

Although the benefits of using VR for improving spatial orientation skills or to measure them were crystallized, the comparison between RW and VR has been rarely made. Most studies focused on spatial navigation, or the participants within the experiments should indicate objects' position by pointing at them instead of active walking (Flanagin et al., 2019; Löwen et al., 2019). The authors stated that performance in VR might differ due to the occurrence of positional shifts of virtual objects (Kelly et al., 2017). Thus, studies already have shown an underestimation of egocentric distances for the coronal, sagittal, and transverse planes (Grechkin et al., 2010; Naceri et al., 2009).

During sports, it is crucial to locate all essential cues such as teammates, opponents, limitations of the playing area, etc., or interact precisely with objects such as rackets, balls, and furthermore. To pronounce VR as a suitable training tool, similar conditions between RW and VR should be presupposed to support the successful transfer of VR attained skills. Therefore, further comparisons should be conducted, and more information about the extraction of visual inputs is needed to strengthen VR used as a supportive method for future training designs. Authors emphasized the importance of visual and spatial working memory capacity in completing environmental tasks such as way-finding (Labate et al., 2014), or map learning (Coluccia, 2008). Several tests were developed to examine the visual and spatial working memory, but how they relate to performance within spatial and environmental abilities is still unclear (Mitolo et al., 2015). Therefore, the second section is dedicated to this problem by comparing active walking in RW and VR. The focus is no longer on navigation using unrealistic translation techniques or descriptions of spatial properties but rather on natural movements, which are desirable for the usage of sport-specific purposes. Today's VR systems (see Figure 2) are limited in their userspace, and up today, there has been no solution for omnidirectional locomotion for private uses. Therefore, the analysis of the orientation ability is mainly limited to the room-scale of the previously used VR application (see 2.1.2).

## 3.3 The importance of the own body visualization in virtual reality

Although VR has been used as a tool to train and refine sport motoric skills, only a handful of studies visualized the whole body. Therefore, it is still unknown to what extent virtual bodies can be perceived as their bodies within virtual environments (Slater et al., 2009). When recommending VR for private uses, it is essential to examine whether the own body visualization is necessary to acquire learning entirely. Within the last few years, VR systems got more comfortable in their usability and affordability. Nevertheless, tracking one's own body requires more than the standard equipment consisted of glasses, lighthouses, and the motion controller (see Figure 2). Such an elaborated setup includes a motion capturing system, which can capture a whole set of markers attached to the user's body enabling the transfer of its skeleton to the humanoid virtual avatar. The movement of the body limbs is then synchronized in real-time, implementing the body's perception. Marker-less systems (e.g., Kinect systems), and inertial measurement units, are also utilized to virtualize the user's body (Caserman et al., 2020), but still hard to reach for private uses.

Previous studies prove that visualizing the body has a positive effect on the performance of the users. This can be generalized through a higher feeling of presence and more realistic conditions (Biocca, 1997). Currently, modeling programs provide predesigned humanoid virtual characters adjusted in terms of structure, morphology, and perspective (Kilteni et al., 2012). Previous findings showed that when participants can choose between the favorite design of different avatars (Mölbert et al., 2018) and when more realistic components are integrated (Caserman et al., 2020), higher immersion and presence are ensured. It was also shown that embodying avatars associated with strength (avatar's appearance) can decrease effort leading to enhanced physical performance (Kocur et al., 2020).

The sensation of presence is a complex interaction of psychological and contextual factors, visuo-proprioceptive coherency, as well as cognitive and sensorimotor aspects (Mestre, 2018). Therefore, it is crucial that the virtual body did not only fit due to similar phenotypic properties, but the acceptance and the sense of body ownership play a significant role in the supportive function of body visualization. Hence, suitable body ownership leads to more accurate movements (Filippetti & Tsakiris, 2017), especially for grasping tasks (Camporesi & Kallmann, 2016) and during lower limb coordination (Kim et al., 2018). Previous findings showed that the virtual body's acceptance does not depend on the equality of one's own body (Latoschik et al., 2017; Steptoe et al., 2013) since the control was still possible. According to different visualization of body shape and size, the behavior and perception of the user changed, especially in social skills (Caserman et al., 2020; Gonzalez-Franco & Lanier, 2017).

Despite the previous illustration, only a few studies considered the effects of whole-body visualization. So far, it was used for therapy (Mölbert et al., 2018) or to investigate cognitive functions in terms of the interaction between body and consciousness (Blanke et al., 2015; Guterstam et al., 2015). The authors presented an overview of the components affecting the embodiment, which is highly associated with concepts of self-location, the sense of agency, and the sense of body ownership (Kilteni et al., 2012; Pastel, Chen, Petri, & Witte, 2020).

In sports, the whole-body visualization has also found application to increase the degree of realism or to decrease cybersickness[9] symptoms. It generates the observation of the own movement execution from different perspectives using a virtual mirror, for example, during squat's completion (Hülsmann et al., 2019). In addition, throwing tasks are better performable with full-user-body visualization (or at least the arms) instead of not visualizing the virtual body (Bodenheimer et al., 2017). Although some intervention studies using immersive VR already showed positive effects (Andira et al., 2019; Petri et al., 2019), the transfer into RW and the influence of body-visualization types are missed. According to Caserman et al. (2020), there is a further need to examine the manipulation of whole-body visualization types and how this impacts users' performances. Many authors emphasized the importance of first-person-perspective (1PP), providing a stronger illusion of body ownership and improved performances (Kilteni et al., 2012; Mendes et al., 2017; Young et al., 2015). Perceiving the VE through the HMD ensures 1PP and is, therefore, popular for research applications. However, it should be emphasized that even with these higher developed output devices, forms of cybersickness still can occur related to the task demands (Curry et al., 2020).

Therefore, the aim of the third section is to investigate whether a reduced body visualization has an impact on participants' performances. Since the whole-body visualization takes place in RW, further comparison of the performances made in both conditions was made to test the suitability and realization of sport-motoric tasks within VEs. Compared to the previously described studies, the participants not only got visual input during the VR experience. While the participants had to conduct each task, they perceived the visual, haptic, and auditive sensory inputs by tracking the virtual body and objects for obtaining real interaction. The software and

[9] Cybersickness can be defined as physical discomfort elicited by the stay in VR. It is elicited through the user's often stationary position who has a compulsive sense of self-motion through moving visual content (LaViola, 2000). Cybersickness is a term that is commonly used to refer to the subset of motion sickness occurring within the perception of VEs (Curry et al., 2020).

hardware components enabling multisensory feedback are described in the initial chapters (see 2.1.1 and 2.1.2).

# Chapter 4

**Hypothesis**

Considering the visual perception analyses within VEs, the present work includes different approaches focusing on comparing visual information processing between RW and VR. In general, this work's central question is whether the visual perception in VR is comparable to RW conditions, keeping in mind to examine whether VR is also suitable for sports-specific usage. Therefore, three different sections are considered individually, ensuring a constructive and sequential way to fill the remaining gap whether and to what extent VR offers a possibility for sports integration.

First, the scientific questions of each section are presented to form statistical hypotheses afterward. Depending on each study, the approach is made both inductively and deductively since the previously conducted studies' contradictory results could not consistently predict similar behavior between the conditions (RW and VR).

## 4.1 Gaze behavior – accuracy and precision

Although ET is often used to analyze participants' visual perception during sports scenarios (Kredel et al., 2017; Pfeiffer & Essig, 2015; Snegireva et al., 2018), it should be emphasized that the collected data of the current study do not reveal any information about the analyses of the visual perception in both conditions. The reason, therefore, is the chosen parameters previously explained, which are extracted from the raw data of each ET system. Instead, it was considered whether the quality of the measurements from the two ET systems matched in terms of both accuracy and precision. To make any statements about the comparison of the visual perception between the conditions, parameters like fixations, saccades, and further eye movement events needed to be calculated by using the raw data. The current study takes a step backward to reveal the validity of both ET systems to conclude further whether the analysis of the visual perception can be executed in the same way. In addition, the study allows verifying whether visual stimuli can be observed/fixated within VR as accurate as in RW.

To extend these analyses to multiple forms of visual stimuli presented in the scene, the different tasks included different kinds such as static (task 1), dynamic (task 2), and varied distanced static (task 3) stimuli. Although high knowledge about ET systems' quality is provided by consistent results of ET studies in RW and by the manufacturers themselves, no study has examined the measurement quality between the conditions that prevents the setting of a directed (one-tailed) hypothesis. Generally, the scientific questions are divided into two main scientific questions.

#### 4.1.1 Gaze accuracy

The first scientific question is whether visual stimuli with different properties could be fixated accurately within a VE to the same extent as in RW. Therefore, a division of the tasks ensures an inductive way to make further statements about the quality of measurement within both environments. This results in the following statistical hypotheses:

Static visual stimuli:

$H0_1$: There is no significant difference between gaze accuracy (distribution of angles in degree) in the real and virtual environment for static visual stimuli.

$H1_1$: There is a significant difference between gaze accuracy (distribution of angles in degree) in the real and virtual environment for static visual stimuli.

Dynamic visual stimuli:

$H0_2$: There is no significant difference between gaze accuracy (distribution of angles in degree) in the real and virtual environment for dynamic visual stimuli.

$H1_2$: There is a significant difference between gaze accuracy (distribution of angles in degree) in the real and virtual environment for dynamic visual stimuli.

Static visual stimuli with varied distances:

$H0_3$: There is no significant difference between gaze accuracy (distribution of angles in degree) in the real and virtual environment for varied distanced visual stimuli.

$H1_3$: There is a significant difference between gaze accuracy (distribution of angles in degree) in the real and virtual environment for varied distanced visual stimuli.

#### 4.1.2 Precision

The second scientific question is whether both measurement systems (ET in HMD and the mobile glasses) capture the participant's gaze with the same precision. In contrast to the accuracy, only two tasks are considered to calculate the precision.

Static visual stimuli:

$H0_4$: There is no significant difference within the precision (distribution of angles in degree) of each measurement system between the real and virtual environment for static visual stimuli.

$H1_4$: There is a significant difference within the precision (distribution of angles in degree) of each measurement system between the real and virtual environment for static visual stimuli.

Static visual stimuli with varied distances:

$H0_5$: There is no significant difference within the precision (distribution of angles in degree) of each measurement system between the real and virtual environment for static visual stimuli with varied distances.

$H1_5$: There is a significant difference within the precision (distribution of angles in degree) of each measurement system between the real and virtual environment for static visual stimuli with varied distances.

## 4.2 Comparison of spatial orientation between real-world and virtual environments

For the evaluation of the spatial orientation within VEs, several tests within two studies are included. Each test has its prioritization, which allows the merge of the results and makes further statements about the equality of spatial orientation between the conditions (RW and VR). As can be seen from the previous chapter 3.2, spatial orientation is composed of several skills. Each mentioned skill helps the individual to orientate within new surroundings. The goal of the two conceptualized studies was to examine different factors of spatial orientation. The factors are:

- distance estimation (verbal and non-verbal)
- route-recreation
- rotation ability
- walking blindfolded to a specific order of different positioned objects[10]

Like observable in the ET study, it is challenging to form hypotheses considering one-tailed analyses since previous findings found differences in the scientific outcome. Nevertheless, the VR devices' features allow the creation of similar environmental conditions, and the simulation could be realized through the 1PP via HMD, which generates high immersion and a realistic transfer from RW to VR. In all tasks requiring direct walking to reach the target the two-dimensional deviation (cm) and time needed to complete (s) are captured to evaluate the trials

[10] To describe this in a more abbreviated way, the term pathway is used below.

and defined as parameters allowing statistical analyses. Therefore, the following hypotheses concerning each parameter are formulated:

#### 4.2.1 Distance estimation

$H0_6$: There is no significant difference in the deviations of distance estimation (cm), neither in verbal nor in walking distance estimations between the real-world and virtual environment.

$H1_6$: There is a significant difference in deviations of the distance estimation (cm), neither in verbal nor in walking distance estimations between the real-world and virtual environment.

#### 4.2.2 Route-recreation

To examine the precision of route-recreation, six reference points (see Figure 10) were chosen. The two-dimensional distance between them and a marker placed on the solar plexus of the participants was measured. The scientific question is whether there is a difference in recreating a previously observed route (duration of 15 seconds) between the real-world and virtual environment. Statistical hypotheses with the following parameters were developed:

$H0_7$: There is no significant difference in the deviations (cm) of each reference point and the marker placed on participants' bodies between the real-world and virtual environment.

$H1_7$: There is a significant difference in the deviations (cm) of each reference point and the marker placed on participants' bodies between the real-world and virtual environment.

#### 4.2.3 Rotation ability

The same way of comparing participants' performances was chosen for the rotation and pathway tasks by using the deviations between the marker placed on participants' index finger and each object's actual position of each object. The scientific question is whether there is a significant difference in walking blindfolded to objects requiring different degrees of rotation between the real and virtual environment. An additional parameter (time in seconds) was added for statistical analyses to expand the expressiveness of the performances.

$H0_8$: There is no significant difference between the deviations (cm) or the time for completion (s) to the objects requiring certain degrees of rotation in the real-world and virtual environment.

$H1_8$: There is a significant difference between the deviations (cm) or the time for completion (s) to the objects requiring certain degrees of rotation in the real-world and virtual environment

#### 4.2.4 Pathways

For the pathways, the question is divided into two main parts, whether the participants can memorize each object's position between the real and virtual environment and whether they can reach them in VR as accurately as in the real condition. The time is also considered in this task.

$H0_9$: There is no significant difference between walking accuracy (deviations in cm) and pace (time in s) to a specific order of objects in the real-world and virtual environment.

$H1_9$: There is a significant difference between walking accuracy (deviations in cm) and pace (time in s) to a specific order of objects in the real-world and virtual environment.

### 4.3 Effects of body-visualization types on performances with sport-motoric tasks

This included study pursues two primary goals. The first one was to determine whether the participants' performances decreased when more body limbs were excluded from vision within three different motoric tasks (balancing, grasping, and throwing). The second aim was to compare the performances between RW and VR. For this comparison, the whole-body visualization was used in VR to generate same conditions and to exclude interfering variables.

#### 4.3.1 Effects of a reduced body visualization on sport-motoric performances

In VR, benefits by excluding body limbs from vision not realizable within the real condition allow further examination of how much of the own body must be perceivable during different task-motoric completion. Therefore, different task-related body limbs were removed from vision in the balance task: the feet (NF), feet and legs (NLF); in the grasping and throwing task: the hands (NH), and no arms and hands (NHA) (see Figure 12). Since the whole-body (WB) visualization demands highly technical equipment, the no-body (NB) visualization was also included to examine whether the motoric tasks are still executable without getting visual feedback of the position of the body limbs. Generally, the scientific question is whether there is a deterioration of the participants' performances during the reduction of task-related body limb visualization in VR. Additionally, it is possible to examine whether the demanded tasks are still doable even when no body is visualized. Different parameters were considered to check this assumption: number of errors, time for completion, and for the balance task, the number of foot strikes was also obtained revealing participants' awareness of being safe during task completion. The subjective estimation of difficulty was measured by using a scale from 0 (no subjective difficulty) to 10 points (very difficult) to further getting an impression of equal completion in both conditions. All these parameters indicate participants' performances, whereas each of them is covered within the defined hypothesis. The following hypotheses are tested for each predefined parameter, which is shown in the result section (see 5.3).

$H0_{10}$: There is no significant difference in the participants' performances during the reduction of task-related body limb visualization in VR.

$H1_{10}$: There is a significant difference in the participants' performances during the reduction of task-related body limb visualization in VR.

### 4.3.2 Comparison of sport-motoric performances between RW and VR

The second aim was to compare the participants' performances between the RW and VR. Therefore, the performance in VR, including the whole-body visualization, was considered for comparison to the RW performance since equal testing conditions were given. The scientific question was whether the motoric tasks can be equally performed within both conditions. This results in following hypothesis considering each conducted task.

$H0_{11}$: There is no significant difference in the participants' performances of the motoric tasks between RW and VR.

$H1_{11}$: There is a significant difference in the participants' performances of the motoric tasks between RW and VR.

Again, each previously defined parameter is considered as performance for the comparison between the conditions. Each parameter is compared separately in the result section.

# Chapter 5

## Publications and Results

The current chapter provides a brief overview of each study's conduction, ensuring a better understanding of the subsequent result presentation. For getting a detailed description, a reference to the appendix is given for each study individually. In all studies, the tasks were completed in RW and VR by the same participants, and the order of beginning in RW or VR was randomized to reduce a sequential learning effect.

Table 1 Overview and assignment to research questions and publications. The colors indicate the previously defined sections (see Figure 5).

| Scientific questions | Publications (appendix A) |
|---|---|
| Section 1 | |
| Comparison of gaze accuracy and precision in real-world and virtual reality (A1) | |
| How accurately can visual stimuli be observed in VR compared to RW?<br><br>How precise are the gaze tracking data captured of the mobile ET system (RW) compared to the integrated ET system in HMD (VR)? | This is an Accepted Manuscript of an article published by Springer in *Virtual Reality* on *03 June 2020*, available online: https://link.springer.com/article/10.1007/s10055-020-00449-3<br>Impact factor: 3.6 |
| Section 2 | |
| Spatial orientation in virtual environment compared to real-world (A2) | |
| Can distances be estimated similarly in VR compared to RW?<br><br>Is it possible to run off a route recreated by memory being aware of the original starting position in RW and VR? | This is an Accepted Manuscript of an article published by Taylor & Francis in *Journal of Motor Behavior* on *09 November 2020*, available online: https://www.tandfonline.com/doi/abs/10.1080/00222895.2020.1843390?journalCode=vjmb20<br>Impact factor: 1.3 |
| Comparison of spatial orientation skill between real and virtual environment (A3) | |
| Can objects be approached accurately in VR compared to RW? | This is an Accepted Manuscript of an article published by Springer in *Virtual Reality* on 04 June *2021*, available online: |

| | |
|---|---|
| Is there a significant difference between the conditions when different degrees of rotations are required? | https://link.springer.com/article/10.1007%2Fs10055-021-00539-w<br>Impact factor: 3.6 |
| Section 3 | |
| Effects of body visualization on performance in head-mounted display virtual reality (A4) | |
| Is there a deterioration of the participants' performances during the reduction of task-related body limb visualization in VR?<br>Is it still possible when no body visualization is provided?<br>Are there differences between RW and VR in terms of movement quality? | This is an Accepted Manuscript of an article published by Public Library of Science - *PLOS ONE* on *21 September 2020*, available online: https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0239226<br>Impact factor: 2.7 |

### 5.1 Gaze behavior – accuracy and precision

This content is dedicated to the first section (see Figure 5) of the current work. Before presenting the results, a rough description of the experimental conduction and setup is given. A detailed description is attached in the appendix (A.1) (Pastel, Chen, Martin et al., 2020).

#### 5.1.1 Conduction

In this study, the participants were pleased to sit in front of a monitor placed on a desk. A chin rest was mounted and installed to each participant's height to ensure comfortable seating during the conduction. The center of the monitor was on the height of the participants' eyes (see Figure 7). Before they started to conduct each task, the system was calibrated using previously created crosses as reference points. In RW, the investigator controlled the calibration method, whereas in VR, the system automatically controlled the calibration.

After the arrangements were made, visual stimuli were presented on the screen such as static ones appearing in different directions (task 1), dynamic ones moving over the screen in the form of an infinity loop (task 2), or again static ones with varied distances (task 3) (see Figure 7).

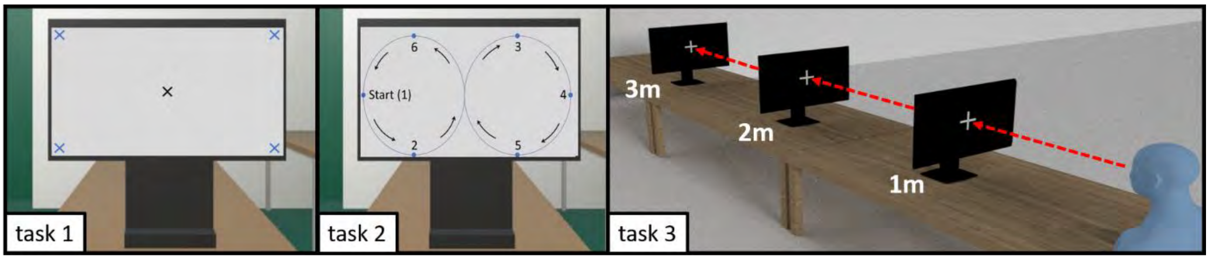


**Figure 7** Overview of the different observation tasks. Task 1 included the observation of static crosses appeared separately in each corner. In task 2, the blue point moved in the form of an infinity loop for 15 seconds. For the analysis, 6 points were considered to serve as reference to determine the gaze accuracy for specific time points. In task 3, the participants fixated the cross in the center of the screen for 3 seconds. The position of the monitor was shifted twice at a distance of 1m. The red arrows indicate the direction of the participants' gaze to the fixation cross placed in the center of the screen (task 3).

Except for task 2, each task was conducted twice. During task completion, the participants were pleased to keep their heads in the fixed position and minimize the blinks to avoid significant ET data quality impacts.

### 5.1.2 Results

The results relate to the previous established hypothesis in 4.1 and are visualized in Table *2*. Particularly, good values of gaze accuracy and precision are reflected in low values, whereas poor accuracy and precision are provided with high deviations (in degree).

Summarized, there are no significant differences regarding the gaze accuracy for static stimuli appearing in different directions. In both conditions, an accuracy of 0.5° (RW=0.55° and VR=0.51°) could be determined. For the cross placed at the center of the screen, a significant lower accuracy could be observed in both conditions, which is in line with previous findings (Hornof & Halverson, 2002).

Table 2 Comparison of gaze accuracy and precision between Virtual Reality (VR) and real-world (RW). The grey marked fields highlight the non-significant difference between the conditions (RW and VR).

| Gaze parameter | Visual stimuli | Hypothesis | Result |
|---|---|---|---|
| accuracy | Static | $H0_1$ is verified | No significant differences between RW and VR were found |
| | Dynamic | $H0_2$ is falsified | The accuracy was significant worse in VR compared to RW |
| | Static with varied distances | $H0_3$ is verified regarding the 1m distance | For the 1m distance, no significant differences were found between RW and VR |
| precision | Static | $H0_4$ is falsified | In VR, significant worse precision was observed |
| | Static with varied distances | $H0_5$ is falsified | In VR, significant worse precision was observed |

For the dynamic stimuli, the accuracy in VR ($M$ = 2.76°, SD = 0.86°) was significant lower compared to RW ($M$ = 0.72°, SD = 0.12°) (see Figure 8). High significant differences are observable, and only reference point number six shows no significant difference between the gaze accuracy in RW and VR. In the last task, in which static stimuli are observed, but the distance of the monitor was shifted, no significant differences between RW and VR are found for the 1m distance. In VR, the accuracy did not change over distance, whereas in RW, it got lower correlated to the increased distance.

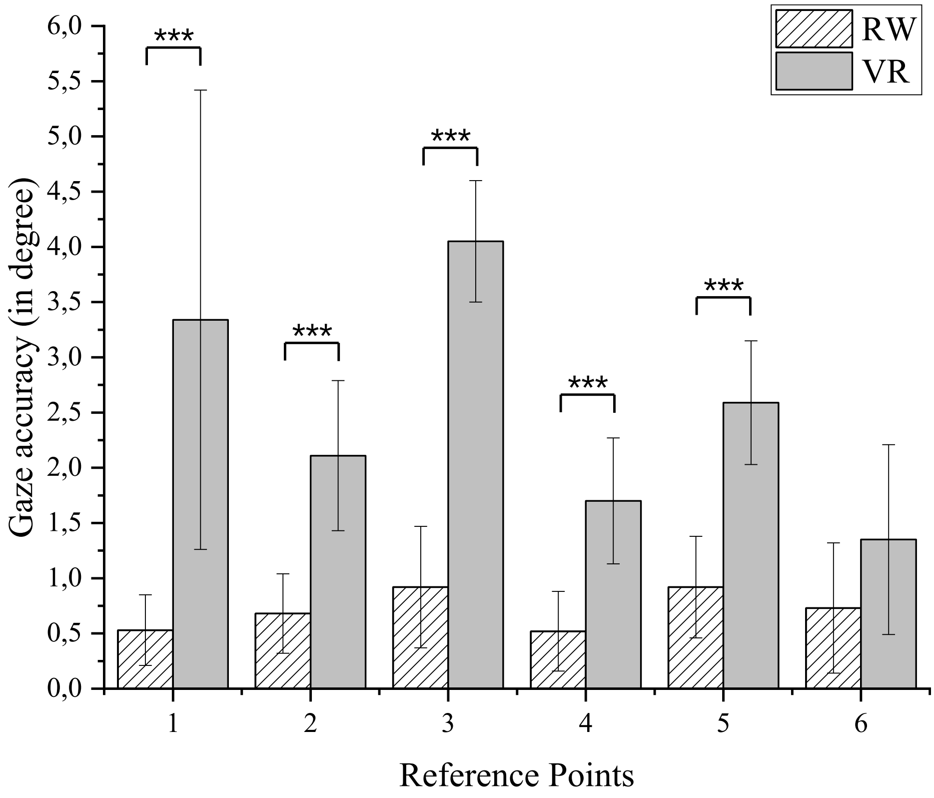


**Figure 8** Gaze accuracy between real-world (RW) and virtual reality (VR) for dynamic stimuli. The gaze accuracy for each reference point (see Figure 7) was calculated, and the means and standard deviation are visualized. The probability of error is indicated through * = $p \leq 0.05$; ** = $p \leq 0.01$; *** = $p \leq 0.001$.

For the precision, significant differences between RW and VR were found for the static stimuli with and without shifted monitor position. In the first task, where crosses placed in different directions should be observed, a significantly lower precision in VR (0.07±0.02) was measured for all crosses compared to RW (0.05±0.02), except for the cross placed at the top left of the screen. The same loss of precision in VR was observed when the monitor's position was changed, whereas the precision in RW remained constantly lower. These differences are not as pronounced as was the case for gaze accuracy within dynamic stimuli.

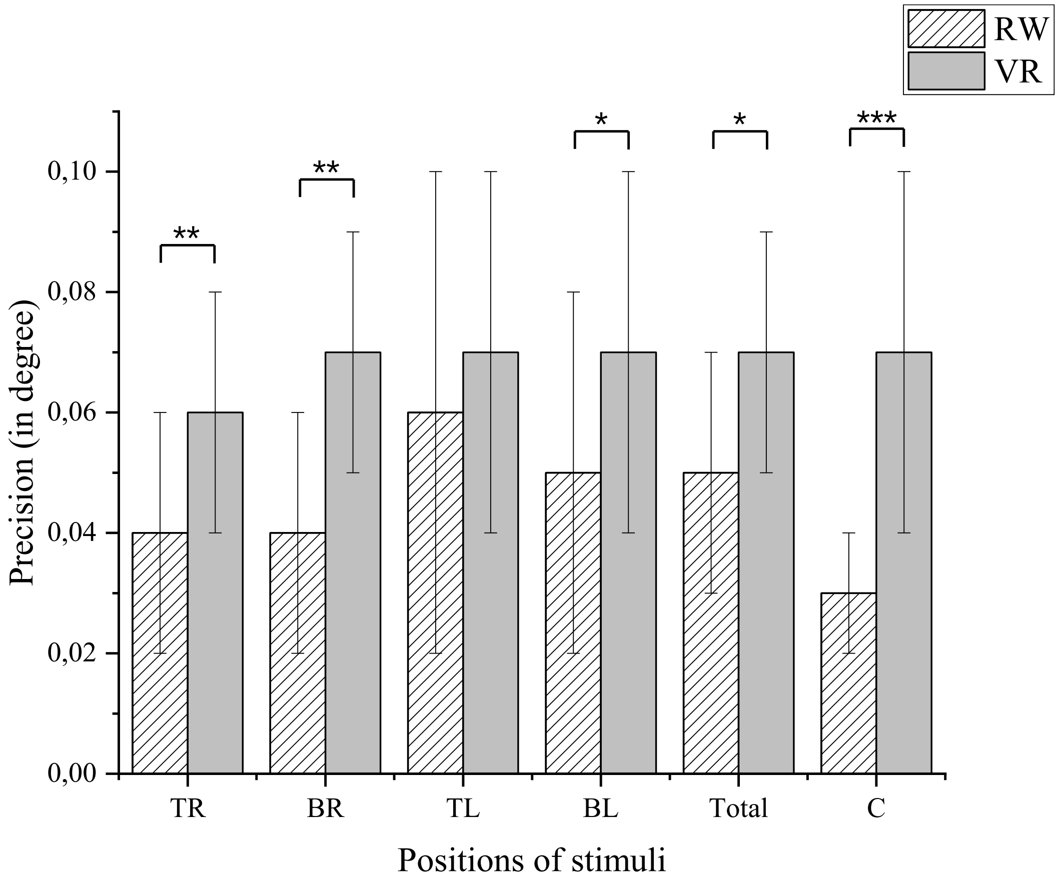


**Figure 9** Gaze precision within real-world (RW) and virtual reality (VR) for static stimuli. The probability of error is indicated through * = $p \leq 0.05$; ** = $p \leq 0.01$; *** = $p \leq 0.001$. The positions of the visual stimuli are abbreviated as follows: top right (TR), bottom right (BR), top left (TL), bottom left (BL), total represents the mean of all stimuli, and c stands for center of the screen.

### 5.1.3 Discussion

The current study aimed to compare the gaze accuracy and precision between the RW and VR during the observation of different visual stimuli. The participants had to conduct three different tasks, in which static, dynamic, and static with varied distanced visual stimuli were presented. The goal was to examine the validity of both ET systems to investigate whether an analysis of the visual perception within VEs can be done without restrictions or differences to the accuracy and precision values that occur in RW.

The gaze accuracy for static visual stimuli can be measured in both conditions to the same extent, whereas dynamic ones were harder to follow with the eyes in VR. The impact of different distances on gaze accuracy was not observable within VR, in which the gaze accuracy remains the same. The precision values were significantly worse compared to RW, affirmed through high effect sizes. A more detailed description is given in the appendix (A1) to understand better how these results were achieved. Here, it is addressed whether the analyses of gaze accuracy and precision still play a role in research and whether future implementations are planned to use accurate and precise measured gaze data.

Generally, letting participants observe different presented visual stimuli is often used to analyze both examined parameters (Feit et al., 2017; Hornof & Halverson, 2002). The interest in the quality of gaze data increased over the last decade since ET systems enable to use gaze data for user interaction and the calculation of gaze parameters revealing insight into the visual perception. Thus, many researchers found that spatial accuracy and precision are the most important data quality measures (B. Adhanom et al., 2020). However, they often report or use the manufacturer's specifications under ideal conditions rather than empirical data to determine areas of interests (AOIs), which could harm the validity of the stated results (Dalrymple et al., 2018). When comparing gaze behavior between RW and VR, or even in VR within the different devices equipped with different ET systems, it is crucial to ensure high data quality. This is required for the comparability and standardization of experimental results (Akkil et al., 2014; Ehinger et al., 2019).

Especially in VR, new ideas come up for further implementations allowing gaze-controlled scenes. Therefore, a method was developed which evaluates the accuracy and precision of integrated ET systems in HMD in different directions inside the VE (Kangas et al., 2020). The authors investigated possible trends over the display areas for optimizing gaze-related interactions. Adhanom et al. (2020) developed a novel open-source tool (GazeMetrics), allowing the measurement of gaze accuracy and precision for various HMD-based eye trackers. This tool can be used inside any existing ET experiment at any time. This is fundamental since the gaze measurements begin to shift over time that is not noticeable after data collection (Ehinger et al., 2019).

The current study shows that there is a significant difference in precision in VR compared to RW. This should be considered since algorithms used in RW to determine gaze parameters such as fixations, saccades, or other eye movement events are not suitable for VR applications. It confirms that the precision of an ET varies with the features of participants' eyes, the system specifies or used calculation methods, and when the measurements are taking place within different environments (Wang et al., 2017). Otherwise, studies report precision values in the range from 0.03° to 1.03° (for remote systems), and values between 0.001° to 1.3° measured from a motionless artificial eye and simultaneously emphasize that tracking real eye will exhibit less precision (Holmqvist et al., 2011; Nyström et al., 2013). Although the existence of significantly less precision in VR has been proven, the values are sufficient for gaze analyses but must be considered within the determination of the characteristics of the algorithms using spatial distribution over time for identifying gaze parameters.

Even though there are already many applications that capture user's gaze data to develop new implementations, the quality of the ET system has not been compared with devices used to measure participants' gaze in the RW. This is surprising since the different determination of temporal and spatial shifting of the PORs may differ in the outcome revealing participants' gaze behavior or superordinated the visual perception. Thus, the present study previews possible differences between the integrated ET system used in VR and the mobile eye-tracker in RW (SMI glasses 2.0). It draws attention to the importance of previous steps needed to ensure valid gaze data, especially during gaze behavior analysis within a VE. Subsequent studies present a solution by developing tools ensuring the measurement of data quality concerning the gaze accuracy and precision. Despite the appeared differences in gaze accuracy and precision between RW and VR, the values are still acceptable for both accuracy (Blignaut, 2009) and precision (Holmqvist et al., 2011).

### 5.1.4 Relevance in the field of sports

In the first section, a study is integrated, of which only a few references to the sport can be drawn since the laboratory setup is limited in terms of the highly dynamic situation during sports. Nevertheless, the gaze accuracy and precision of the ET system integrated into an HMD play a crucial role in terms of the application fields. Both parameters are the data source used to calculate algorithms to determine visual perception indicators, such as fixations, saccades, etc. It is fundamental to determine the spatial and temporal characteristics of the gaze parameters since different definitions could lead to different results (Llanes-Jurado et al., 2020; Pastel, Chen, Martin et al., 2020). The current study shows that fixed stimuli in VR can be accurately observed, comparable to those in RW. Although the precision values are significantly higher than in the RW, they are still acceptable for determining gaze parameters defined by the spatial distribution over time. All the methods listed below rely on gaze accuracy and precision of the ET systems, and therefore, play a crucial role for future implementations into sports. In general, the ability to measure the gaze behavior of athletes/users in VR offers many exciting applications to gain certain training forms or knowledge around the visual perceptional processes.

The visual perception has been researched for a long time and becomes increasingly important, especially in sports science. At the current time, it is not clarified how increased visual perceptional skills lead to significant improvements in athletes' performances and to what extent experts are superior to novices. Some positive findings show differences within the sensory, motor, and perceptual aspects of basic vision, including visual resolution (dynamic visual acuity), static visual acuity, contrast sensitivity, depth perception (stereopsis), visual tracking (vergence, pursuit, saccades, and fixation), visuomotor integration (eye-hand coordination, reaction times, speed discrimination and temporal processing, decision making, peripheral awareness (Ciuffreda & Wang, 2004; Mann et al., 2007; Poltavski & Biberdorf, 2015). The authors also state contradictory results that advanced athletes do not differ from novices in terms of static or dynamic visual acuity (Bulson et al., 2008; Ward & Williams, 2003), speed or span of recognition, and visual reaction time (Classé et al., 1997). Despite the non-concurring results, a trend to develop visual training scenarios increased over the last decade, primarily through new technologies.

Although many training applications are already used to improve visual acuity, peripheral awareness, eye-hand coordination, such as dribbling tasks or precision shooting (Junyent, 1995; McLeod, 1991), previous work refutes the effect of visual training (Abernethy, 1986; Wood & Abernethy, 1997). Authors emphasize that many negative findings are caused by a lack of standardization of the measurement techniques, testing conditions, outdated instrumentations, and protocols (Erickson et al., 2011). Therefore, systems were developed which test the basic visual and information processing skills of athletes, such as the Nike SPARQ Sensory Training Session (Erickson et al., 2011). These negative findings are more related to the studies' set-up, whereas the training itself contributes to the improvement of performance. Thus, a recent study showed that visual training has its justification since many improvements of skill level resulting from enhanced visual system capabilities such as visual acuity or dynamic visual activity (Clark et al., 2020).

VR would address many of these previously described problems. For determining athletes' levels or to develop a vision training tool, VR is predestined for the following reasons. The lack of standardized measurement techniques, testing conditions, protocols, etc., can be avoided through the benefits of object-orientated programming, which brings new opportunities to design training concepts equal for all participants or adaptable to individual skill levels. The modulation of attention is crucial for the majority of competitive sports (Di Russo et al., 2003), which can be easily realized within the VE. For example, the attention on relevant visual cues of the opponents' attacks or shifting to the main structure of movement during learning is crucial and should be incorporated within any sports vision training paradigm (Ciuffreda & Wang, 2004). In VR, this can be highlighted using a change in contrast or lighten areas of the observed athlete. Detecting the participants' gaze in real-time enabled through the integrated

ET system indicates where the participants are looking and how their attention can be controlled or shifted to the essential cues. A significant benefit of VR could also be the possibility of the interaction or reaction of visual stimuli appearing within a full-immersive environment, which is more realistic instead of sitting in front of two screens which is the case for most developed vision training programs. The measurements of visual perceptual abilities within more realistic conditions allow more conclusions about the transfer to RW performances.

Thus, this combined technic's primary role is the possibility to measure the visual perception within any desirable sport-relevant situation. This is accompanied by using the VR benefits to standardize the test conditions, such as the visualization of athletes' performances from a three-dimensional perspective or being immersed in different game situations allowing visual training concerning tactical improvement. Previous findings offer a solution how to generate visual perceptual parameters within VEs, such as fixations in correlation with the recognition of spatial information (Kim & Kim, 2020) or with a focus on color perception (Cohen et al., 2020), speed of gaze (Sitzmann et al., 2018), saccades for the development of an infinite walking method (Sun et al., 2018) or for identifying visual search strategies (Piras et al., 2014), and VAC (Iskander et al., 2019; Klinghammer et al., 2016) to examine how humans are using allocentric information for memory-guided reaching of visual targets in depth.

Other ideas come up to use this combined technic allowing new implementations relevant concerning sport-specific usage. Detecting participants' POR over space and time allows the development of higher implementations which would be quite useful in sports. Thus, many researchers have already worked on different approaches using ET in VR. Detecting saccades allows to include infinitive walking methods that enable running through any imaginable sport situation without interruptions caused by the limited physical space in the RW (Sun et al., 2018). Since the most extensive visual acuity lies in the retina center, many studies have taken advantage by developing foveated rendering (FR) methods, which leads to more realistic visualization of the VE without needed higher computational power (Meng et al., 2020; Patney et al., 2016; Roth et al., 2017; Weier et al., 2018). FR is used to reduce the quantity of data but facilitates higher fidelity and real-time rendering, maintaining low latencies, which leads to better immersion and less motion sickness (Roth et al., 2017; Weier et al., 2018). The authors emphasized that ET systems have to sufficiently deliver high accuracy and precision values to prerequisite perceptual requirements. Therefore, previous development of simulation software was made, which identifies the gaze accuracy and precision within ET systems integrated into HMD to reveal the quality of gaze data and see possible trends over the display area (Kangas et al., 2020). The current study shows sophisticated accuracy within the center of the FoV, which is in line with other results (Hornof & Halverson, 2002). This advantage enabled through the integrated ET system could increase usability, as many users might not be able to afford new expensive hardware components realizing smooth visualization of high realistic VE. However, this would require that the integrated ET systems become cheaper, and all VR devices must be equipped with such a system.

Nevertheless, this form of combined technology could be of great use in sports science. Previous findings show the possibility to track participants' gaze enables the determination of the quiet eye duration supporting movement execution (Causer et al., 2010) or predictive eye movements to examine the anticipatory skill (Mann et al., 2019). Generally, ET in VR has been rarely used in the context of sports, whereas Mann et al. (2019) examined predictive saccades during the participants hit a bouncing ball. The authors ascertained that predictive saccades direct the gaze above the location at which the ball will bounce, ensuring suitable ball tracking after the touch of the ground. In sports, it is usual to move not only the eyes but also head or body movements are initiated to complete the movement. Hereby, the new system supports practical use by ensuring less affected shifts triggered by head movements due to more stable mounting on participants' eyes or the prevention of external lights, which can also harm the ET data quality (Sidenmark & Gellersen, 2020). Ensuring accuracy can also be ensured by methods detecting predictive eye movements, even when the position of the HMD changed relative to the position of the user's head (Shi et al., 2020).

## 5.2 Spatial orientation

This chapter is dedicated to the second section (see Figure 5) of the current work. Before presenting the results, a rough description of the experimental conduction and setup is given. A detailed description is attached in the appendix (A.2, A.3). Two papers are included examining spatial orientation skills between RW and VR (Pastel et al., 2021; Pastel, Chen, Bürger et al., 2020).

### 5.2.1 Conduction

The first paper includes two studies in which the distance estimations (1) and the route-recreation task (2) were performed. In the second paper, the ability to rotate and the analyses of pathways (3) were tested (see Figure 10).

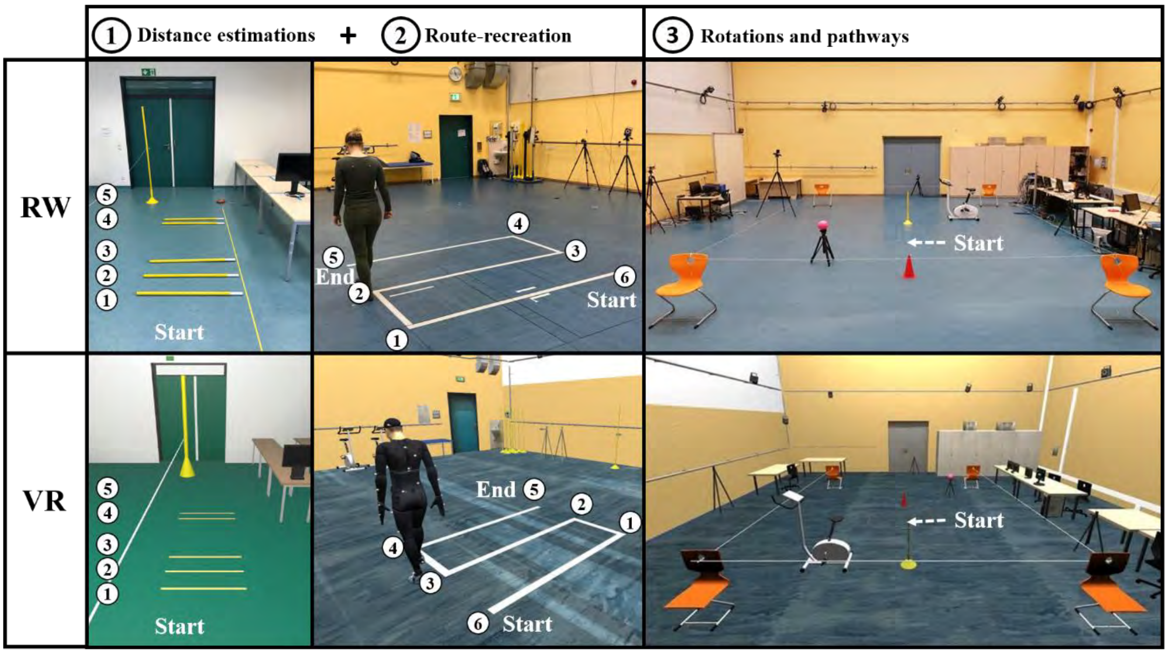


**Figure 10** Overview of the tasks measuring the spatial orientation ability. The upper row shows the real-world setup (RW), whereas the bottom row indicates the tasks within the virtual reality (VR). For the distance estimation task, each number represent one distance that should be estimated by the participants: 1 = 0.9m, 2 = 1.2m, 3 = 1.5m, 4 = 2.6m, and 5 = 2.8m. For the route recreation task, the numbers indicate each measured time point. Hereby, the deviation from the participant's route to the fixed route on the ground was calculated and later used for statistical analyzes.

In the distance estimation task, the participants were pleased to estimate verbally five different defined distances (in m). Therefore, they observed the line lying in front of the ground from a fixed starting position (Start). Each distance was estimated twice. After each verbal distance estimation was absolved, they were pleased to walk blindfolded to each previously estimated distance (the deviations measured in cm from the top of the feet to the line).

The route-creation task was to stand at the starting position (Start) and to observe the route for 30 seconds. Afterward, the vision was covered, and the participants should follow the route as accurately as possible. When they believed having arrived at the end (see Figure 10, 2 Route-recreation), they should return to the starting position (Start).

In the next manuscript, the study examined the ability to rotate and walk accurately to different placed objects in a real and virtual environment. In the rotation task, the participants were pleased to move to the testing area center (see Figure 10, 3 rotations and pathways). From this position, the participants were pleased to fixate the first object for 15 seconds. Afterward, the vision was covered with a blindfold (in VR, the screen was blacked), and they should first rotate clockwise and then walk as accurately as possible to the previously fixated object. To indicate the suspected position, they were pleased to use their index finger that was equipped with a passive marker for optimal position tracking captured by the motion capturing system (Vicon Nexus). In the end, they were guided back via circuitous routes avoiding feedback of performance. This procedure was repeated for every single object twice. The second run was conducted after the pathway task, which is described in the following paragraph.

In the pathway task, the participants observed the testing area for two minutes. They were allowed to go through the scene, changing the perspectives but should not touch any object. The order of objects was changed from the starting condition to the following to reduce learning effects and increase the participants' motivation. After the observation was completed, they turned to the starting point (the same position as in the rotation task). Again, the vision was covered with a blindfold, and the investigator guided them to a new perspective (see A.3). From this perspective, they should walk to two previously named objects. As soon as the participants thought they had reached the first one (indicating the object's position with the index finger), they should move on to the next remembered object on their initiative. After reaching the second object, they were guided back via circuitous routes similar to the rotation task. This procedure was repeated for two further pathways (for more see A.3).

### 5.2.2 Results

The results are divided into four sections related to the hypothesizing.

Table 3 Comparisons of the spatial orientation between real-world (RW) and Virtual Reality (VR). The grey marked fields indicate the maintaining of the $H_0$, which are created in Chapter 4.

| Parameter | Hypothesis | Results |
|---|---|---|
| Distance estimation | $H0_6$ is verified | There are no significant differences for the verbal and non-verbal distance estimations between RW and VR |
| Route-Recreation | $H0_7$ is falsified | There are significant differences in the deviations of references point of the route between RW and VR |

| | | |
|---|---|---|
| Rotations | $H0_8$ is verified | There are no significant differences of the deviations or time duration within the degrees of rotation between RW and VR |
| Pathways | $H0_9$ is verified | There are no significant differences of the deviations or time duration within the degrees of rotation between RW and VR |

### 5.2.3 Discussion

One of the primary goals of the first considered study was to examine whether verbal and non-verbal distance estimations can be equally absolved in both conditions (RW and VR). In the same study, another test measuring the ability to recreate a route via blindfolded walking was integrated to make further statements about the visual-spatial skill in both conditions.

The results show that equal estimations can be completed within VR concerning the mentioned distances (0.9m – 2.8m) for distance estimation. To strengthen the quality of distance estimation, verbal and walking estimations were tested, which were also examined by previous studies (Messing & Durgin, 2005). Both could be equally performed between RW and VR (see Figure 3, Appendix A.2).

Generally, researchers found an impact on distance perception elicited through graphical quality (Thompson et al., 2004), FoV (Knapp & Loomis, 2004), and display weight (Willemsen et al., 2009). Recently, different studies compared modern and older models of HMDs in terms of the perceived space in virtual environments (Creem-Regehr et al., 2015; Kelly et al., 2017). Kelly et al. (2017) also used the HTC Vive for the visualization, which facilitated more accurate estimations of different distances than older devices and no differences in estimation quality taking place in the RW. The often observable underestimation can be reduced by higher resolution of the HMD display (Kelly et al., 2017). Kunz et al. (2009) mentioned that graphical quality impacts verbal distance estimations instead of walking ones. A survey on depth perception in HMDs was made, and contributions for improvement of depth perception and specifically distance perception are presented (El Jamiy & Marsh, 2019). A further study examined VR experiences by letting the participants blind-walk to a VR target 2.5 meters away and found that participants equipped with a scale-matched avatar show a reduced underestimation of distances (Gonzalez-Franco et al., 2019). An improved distance estimation by realizing a self-avatar is also found in previous studies which showed refined walking behavior (McManus et al., 2011; Phillips et al., 2010). Interactions such as the heights of stepping over and under obstacles (Lin et al., 2012) or, more carefully feet placing (Kim et al.,

2018) are easier to complete. A further study could show that the occurred underestimations and object size judgments are also reduced due to interaction with feedback for a larger scale (up to 11 meters) (Siegel & Kelly, 2017). Overall, all distances could be equally estimated in both conditions, and no full-body visualization in VR was necessary to reach the level of RW.

Considering the route recreation task, the participants had to walk blindfolded as accurately as possible on the ideal route. After achieving the end, they should return to the assumed starting position. The ability to reach the original starting position is a high indicator to check whether the participants got the same visual input of each presented environment in terms of distance estimations, depth perception, and the space magnitude, and is, therefore, suitable for spatial orientation measurement (Notarnicola et al., 2014). The results show that the participants differ in deviations to each reference point at the middle of the route (points 3 and 4, see Figure 10). The remaining reference points and the ability to return to the starting position were accurately reached by the participants in RW and in VR. No significant differences could be found in the distance (cm) between the installed passive marker and the original coordinates of each reference point ($p>.05$) in both conditions.

In research, route-recreation tasks are mainly considered by examining the role of landmarks on cognitive maps, where the participants had to follow navigational cues along a fixed route. This can be performed by natural or non-natural walking using a gaming controller (Bruns & Chamberlain, 2019), facilitating teleporting (Cherep et al., 2020). Preferably, most studies concentrate on spatial memory and building up cognitive maps with the purpose of daily navigation through new surroundings (Lew, 2011; Wiener et al., 2020). Authors describe cognitive mapping as a complex process, which enables the individual to encode and store spatial information through sound, cultural, and knowledge about the structural form and elements in space (e.g., Bruns & Chamberlain, 2019). Recreating a route, configural survey knowledge consisting of route or procedural knowledge is necessary to distinguish broader spatial relationships (Chrastil & Warren, 2015). However, many studies already used VR as a tool to examine spatial orientation skills of people exploring new surroundings (Bruns & Chamberlain, 2019; Wiener et al., 2020), and additionally between different age groups (Allison & Head, 2017), without considering a comparison between RW and VR or a possible transfer in RW. Nevertheless, VR is a usable and practical tool to evaluate spatial orientation ability and improve visually simulated reference frames (Nguyen-Vo et al., 2018). The present study shows that the participants were able to encode similar spatial information within both environments. Although the middle part of the route was less accurately retrieved in VR, the participants could correct their shifts and return to the starting position equal to RW.

In the second study, the participants were asked to walk blindfolded to different placed sport-specific objects after observation. To be more specific, it was tested whether they were able to build up an internal cartographic representation of the surrounding environments equally (in RW and VR). For the rotation task, the participants require the egocentric references systems to specify location and orientation relative to the observer (Wolbers & Wiener, 2014), also known as the dominant system determining objects' positions (Battaglia-Mayer et al., 2003). Instead of letting the participants point on the assumed objects' positions, which is a commonly used method (Flanagin et al., 2019; Kimura et al., 2017), they had to walk actively without getting visual feedback.

The results show that this can be equally performed in both conditions since no significant differences were found nor for the two-dimensional deviations (in cm) from participants' index finger (used as the indicator) to each object's position and either in time for completion for both rotation and pathway task. During the observation phase, the participants collected spatial information and could retrieve it from memory, often related to mental imagery (Chiquet et al., 2020). Research has been done in which the participants retrieve spatial information by fixating on empty locations associated with task-relevant stimuli (for example, objects) (Kumcu & Thompson, 2020; Scholz et al., 2018). However, this differs slightly from the current study since the vision was covered completely. Nevertheless, the mental imagery (MI) and visual memory processes within both conditions (RW and VR) show no significant differences in both tasks. In VR, the participants were able to interactively control their view what creates equal conditions to RW (Makransky et al., 2019). The results imply that MI and visual memory processes work at the same level, including depth cues (e.g., texture and perspective) and visual input (e.g., edges, walls) (Chiquet et al., 2020). This is in line with previous findings, which show that VR can be used for improving visual scanning, mental rotation, visuo-construction, visual memory retrieval and reduced memory complaints even for patients suffering from hemi- or quadrantanopia after stroke (Dehn et al., 2020).

Recently, the purpose of new research is to develop methods that allow for rotating in a virtual space without initiating rotations in the real physical world by blurring the screen (Budhiraja et al., 2017) or through the integration of new hardware such as the "NaviChair" or "NaviBoard" (Nguyen-Vo et al., 2021). Accordingly, for applications in which rotations are made both in RW and VR, no problems seem to occur concerning CS, disorientation, or depth information. Traditional locomotion techniques such as using HTC Vive controller show a significant impact on task performance, task load, and CS, whereas the others reveal no significant differences compared to natural walking. This could increase VR systems' usability and expand the application since using VR for private use is always accompanied by restricted physical space in RW conditions.

### 5.2.4 Relevance in the field of sports

Within sports, spatial orientation is crucial to perform motor tasks adequately. These motions usually have to be performed at a high pace due to situational time pressure. This is not only accomplished by sensory input but memorizing supports performances in a goal-orientated manner. This can be, for example, goal-directed passes to a teammate who is not directly in the visual field or the position of the opponents that has to be considered during movement initiation.

Before VR is integrated into sports, it should first be checked whether the manipulation of human perception (the virtualization of the environment/situation) evokes similar actions that would appear in the real-life. Taken into account the output from the two conducted studies, the spatial orientation skills did not differ significantly between RW and VR. However, these statements only apply to static objects since the blindfolded walking related to objects or routes placed on fixed positions. It should also be checked whether the reaction to dynamic stimuli or the interaction with them takes place in the same way that would be of great interest for sports applications. A deeper look in the literature reveals that VR is used for training scenarios in which peoples' task was to cross a road and react to dynamic stimuli under different constraints (Sobhani et al., 2017). Sport-related interaction with virtual objects was also examined in which participants had to catch a ball that has been successfully done by the participants (Pan & Niemeyer, 2017). These results support the interaction with dynamic stimuli within VEs, but there is still a need for more testing conditions.

Whereas only a few studies exist which investigated the interaction with dynamic objects, more has been researched in the field of infinite locomotion in VR. A different navigation method was developed that simulates movement enabling immersive travel and is useful for applications that require jogging (Lee et al., 2018). Other methods that let the participants walk in circles in the RW while still walking straight in VR (Auda et al., 2019) could benefit sports usage. Natural walking behavior ensures high correlations to sports and support body activities to profit from physical training. Therefore, VR applications allowing walking, running, and jogging encourages athletes/patients to physically train within a VE (Ali et al., 2017), such as bimanual coordination (Norouzi et al., 2021), balance, and orientation by stimulating the responsible sensory cues (Bruin et al., 2010), or psychomotor skills (Lehmann et al., 2005).

The studies examining the spatial orientation ability within VEs presented in this work approve the VR usage in terms of tasks that require accurate movements to fixed objects which often plays a role during different training interventions. For example, developed functional obstacle course (Bishop et al., 1999; Means, 1996) or speed court applications allowing the training of explosively changes of direction with a maximum rotation of 180° (Düking et al., 2016) could be easily transferred and realized in VR. Additional feedback such as remaining time, sound, other graphical components, and indicating the next area to be reached can maximize the attention and push the participant to beat the individual record. Room scanning could be the solution, that this VR application is transferrable to each build-up physical world. The SpeedCourt (GlobalSpeed GmbH, Hemsbach) consists of a platform (5.25 x 5.25 m) that is also possible for VR applications. Rotations, distance estimations, and memorizing specific order of objects can be equally done considering this space size (Table 3) and is therefore imaginable to include in private training sessions.

### 5.3 Body visualization

This chapter is dedicated to the third section (see Figure 5) of the current work. Before presenting the results, a rough description of the experimental conduction and setup is given. A detailed description is attached in the appendix (A.4) (Pastel, Chen, Petri, & Witte, 2020).

#### 5.3.1 Conduction

This study aimed to investigate the influence of a reduced body visualization (Figure 12) during the completion of three different motoric tasks, such as balance, grasping, and throwing tasks (Figure 11). In addition, the comparison between the WB visualization in VR and the performances in RW was made to examine further whether those tasks can be completed at the same level.

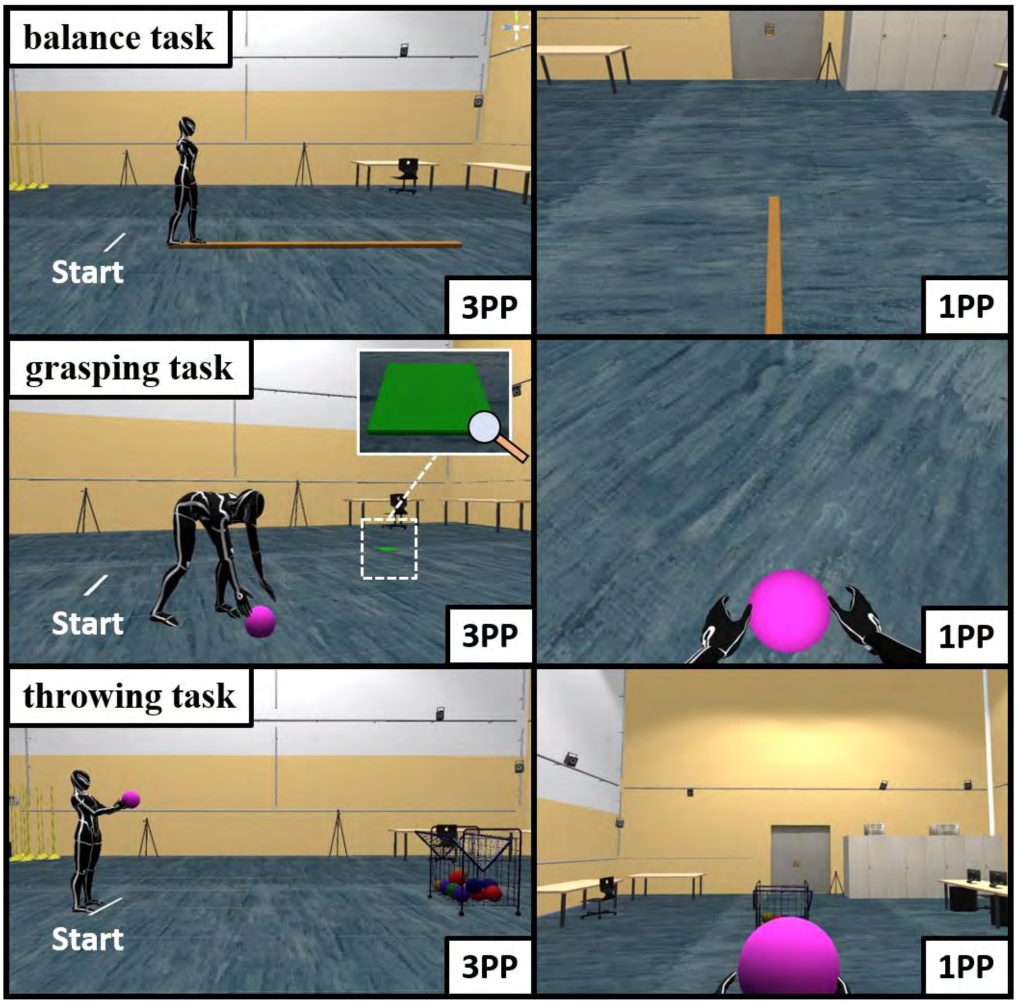


**Figure 11** Overview of the motoric tasks the participants had to conduct. The first-person perspective (1PP) is presented on the right side next to the related task, which are presented in the third-person perspective (3PP) for getting better impressions. All pictures included the whole-body visualization, and the female avatar's body is shown that was adjusted to the participant's gender individually.

Contrary to the other studies, the participants started within the VR condition to ensure a more comfortable procedure. After installing the technical equipment, the participants were pleased to adjust to the VE by exploring it for two minutes. Afterward, the balance task was completed first, followed by the grasping and the throwing task in the end. For all tasks, the participants were instructed to complete the tasks as fast but also as accurately as possible.

Before starting with the balance task, the participants had to perform 10 test trials in which they got familiarized wearing the HMD and the motion capturing suit. Besides, considering the high-level technical prerequisites, it is unusually to act in a VE, including haptic feedback provided by the balance beam, which was also tracked by the infrared-camera system. After finishing the test trials, they should balance over the beam twelve times where different body visualization types (BVT) were provided (Figure 12). Within the balance task, the BVTs whole-body visualization (WB), no legs and feet (NLF), no feet (NF), and no-body (NB) were chosen to examine the possible impact on participants' performances.

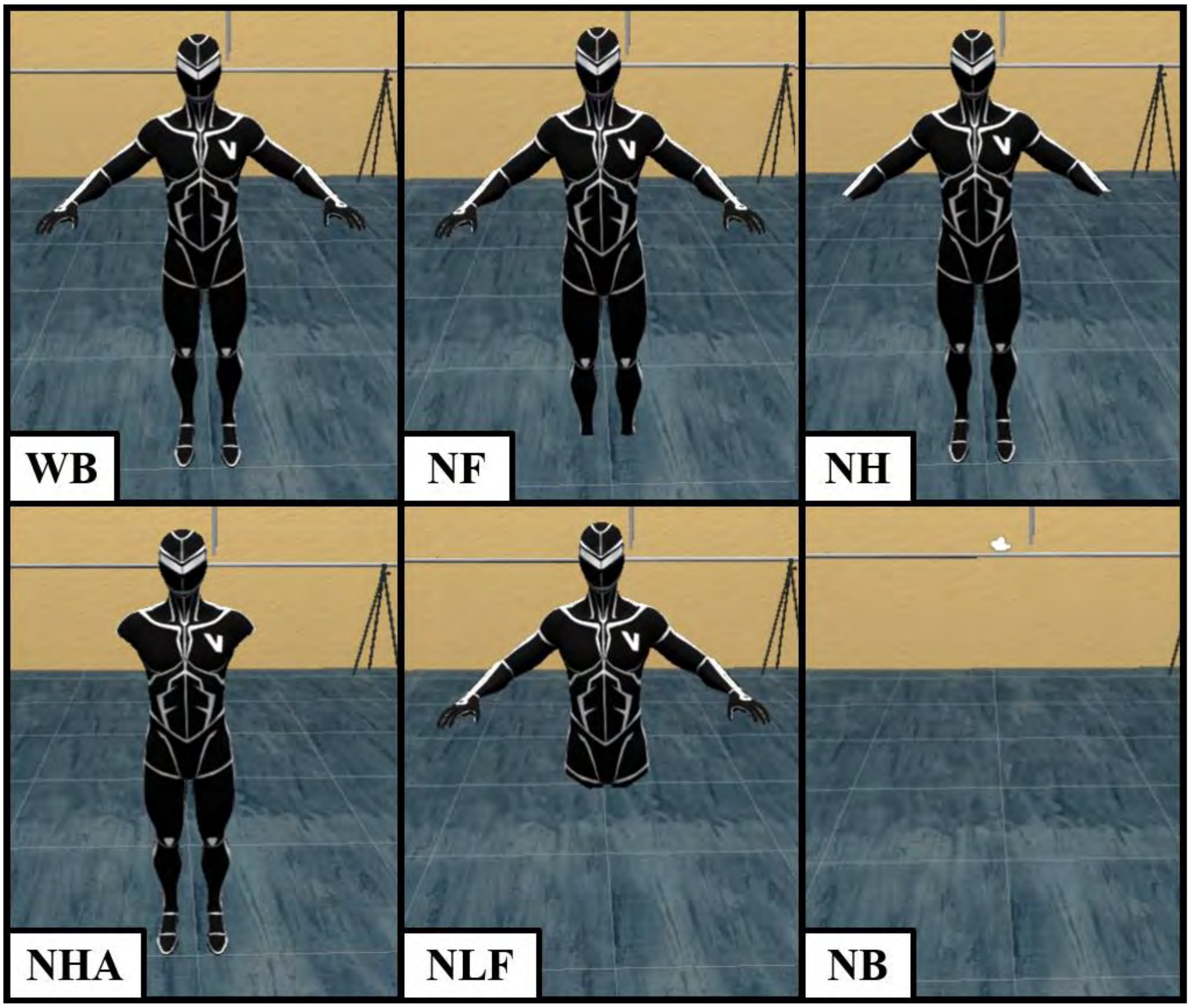


**Figure 12** Overview of the different body visualization types: whole-body visualization (WB), no feet (NF), no hands (NH), no hands and arms (NHA), no legs and feet (NLF), and no-body (NB). The male avatar's body is presented.

### 5.3.2 Results

The first section concentrates on examining whether an increased loss of visually perceivable body limbs leads to an increased reduction in movement performances within each motoric task (Table 4).

Table 4 Effects of a reduced body visualization on performances. In the balance and throwing task, the best performances occurred when the whole-body was visualized. The grey marked fields indicate the acceptance of the $H_0$ previously defined.

| Task | Parameter | Hypotheses | Result |
|---|---|---|---|
| Balance task | Time for completion | $H0_{10}$ is verified | A significant difference in performance for all parameters has not emerged due to increased visual reduction of body segments. Nevertheless, the worst performance results when no body was visualized |
| | Number of foot strikes on the beam | $H0_{10}$ is verified | |
| | Number of errors | $H0_{10}$ is verified | |
| | Subjective estimation of difficulty | $H0_{10}$ is verified | |
| Grasping task | Time for completion | $H0_{10}$ is verified | For all parameters, no significant differences in performances occurred by a reduced body visualization |
| | Quality due to scoring system | $H0_{10}$ is verified | |
| | Subjective estimation of difficulty | $H0_{10}$ is verified | |
| Throwing task | Quality due to scoring system | $H0_{10}$ is falsified | A significant drop in performances occurred by a reduction of the body visualization |
| | Subjective estimation of difficulty | $H0_{10}$ is falsified | |

During the balance and grasping task, no significant increased loss of performance was observable by a stepwise reduced body limb visualization. However, the participants needed significantly more time, took more foot strikes over the beam, and made more errors when NB visualization was provided during the balance task. This is not transferrable for the grasping task since no significant differences occurred even for the NB visualization.

In the throwing task, a significant decrease of performances elicited through the reduced body visualization occurred. Hereby, a sequential reduction of the body parts also led to a sequential loss of movement quality (see Figure 13). As a result, the best performances were obtained while perceiving the whole body, whereas the worst is observable during the NB condition. The tasks were estimated significantly harder if the WB visualization has been waived. This has also led to several failed throwing attempts.

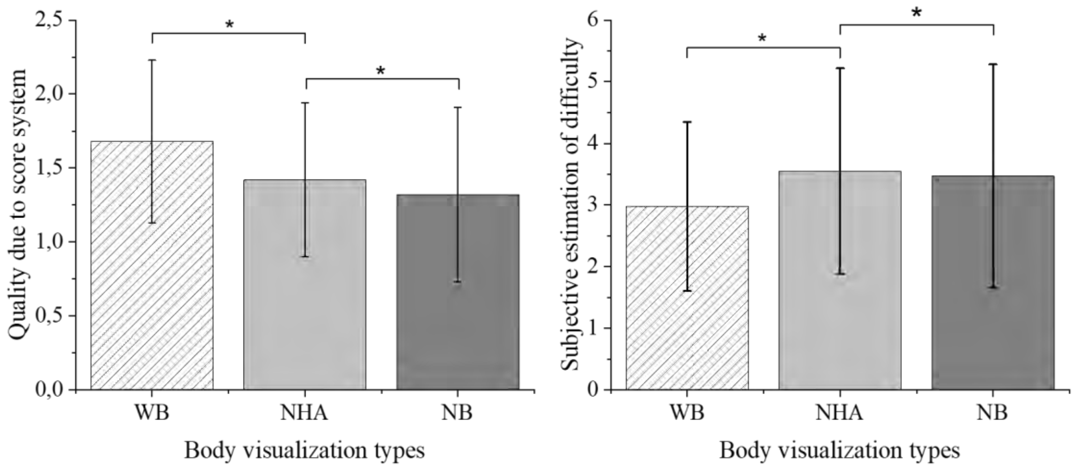


**Figure 13** The influence of body visualization on participants' throwing performance.

For the comparison between the performances within RW and VR, only the WB visualization type was considered due to standardized testing conditions (Table 5). The primary focus here is on checking whether the tasks can be equally completed in terms of time for completion, the number of errors, and subjective estimation of difficulty in both conditions.

Table 5: Difference of the performances between RW and VR. The grey marked fields indicate the acceptance of the $H_0$ previously defined.

| Task | Parameter | Hypotheses | Result |
|---|---|---|---|
| Balance task | Time for completion | $H0_{11}$ is falsified | In VR, the participants needed significantly longer for task completion (large effect) |
| | Number of foot strikes on the beam | $H0_{11}$ is falsified | In VR, the participants took more foot strikes on the beam (large effect) |
| | Number of errors | $H0_{11}$ is verified | No significant differences between RW and VR |
| | Subjective estimation of difficulty | $H0_{11}$ is falsified | In VR, the tasks were estimated significantly as more difficulty than in RW (large effect) |
| Grasping task | Time for completion | $H0_{11}$ is falsified | In VR, the participants needed significantly longer for task completion (large effect) |
| | Quality due to scoring system | $H0_{11}$ is verified | No significant differences between RW and VR |
| | Subjective estimation of difficulty | $H0_{11}$ is falsified | In VR, the tasks were estimated significantly as more difficulty than in RW (large effect) |
| Throwing task | Quality due to scoring system | $H0_{11}$ is verified | No significant differences between RW and VR |
| | Subjective estimation of difficulty | $H0_{11}$ is falsified | In VR, the tasks were estimated significantly as more difficulty than in RW (moderate effect) |

The results show that all three motoric tasks can be executed without an increased number of errors or significant differences in quality ascertained by the scoring system since no significant differences were found between RW and VR. However, it is noticeable that the participants seemed to have acted more cautiously in VR since longer time durations or more steps over the beam have been taken. This can be confirmed by the significantly higher subjective estimation of difficulty that occurred in VR.

### 5.3.3 Discussion

The current study followed two aims. The first aim was to examine how much of the body must be perceivable to complete three sport-motoric tasks without losses in movement performance, such as balancing, grasping a ball, laying it on a target at different distances, and throwing a ball into a ball cart. The second aim was to compare the participants' performances in VR to those in RW since previous studies report contradictory conclusions of the movements' quality executed within a VE.

The current study results show that a visualization of the body seems to positively affect the participants' performances since the worst performance occurred when NB was visualized. This can be explained through the behavioral and psychological effects caused by embodiment increasing the user's experience and performance (Lugrin et al., 2018). The benefits of a virtual body are confirmed in other studies, such as a higher sense of danger. The authors also examined the effect of varying the number of visible body parts categorized in no visible body parts, low meaning only hands and forearms, and medium defined as a visible body with head, neck, trunk, forearms, hands, and tail for the lower body parts. Interestingly, they reported no significant differences between the three body visualization types for virtual body ownership, game experience, and performance, which is not in line with the results of the current study and other findings (Camporesi & Kallmann, 2016; Filippetti & Tsakiris, 2017; Kim et al., 2018; LaViola, 2017). The reason, therefore, could be that the level of immersion is mostly driven by sensorial immersion, and the lack of focus on the avatar body is caused by autotelic activities (Lugrin et al., 2018), which is in line with other researchers who observed an experience of a sense of body ownership and/or agency even when no virtual body parts are presented (Murphy, 2017). Lugrin et al. (2018) used a visible body with hands and forearms, whereas in the present work, a reduction of the body parts took place. To address the question of how much of the body must be visualized to complete sport-motoric tasks, only the visualization of the feet for balancing or only the hands for the grasping and the throwing task should be considered to fully understand the importance of visual feedback of the task-related body limbs.

Generally, positive effects such as improved distances estimation (Ries et al., 2008), spatial knowledge (LaViola, 2017), connectedness to the VE (Interrante et al., 2006), and less cognitive load (Gonzalez-Franco & Lanier, 2017; Steed et al., 2016) are reported when at least a few body parts are visualized. Through this, an increase in the user's movement accuracy can be ensured (Lugrin et al., 2018). This is in line with the results presented currently since the best performance was made when the WB visualization was provided. Nevertheless, to ensure full-body illusion in VR, a lavish setup with high technology components is needed and not available for every single user. Therefore, it is crucial to determine whether single body parts are sufficient to ensure a high embodiment and complete motoric tasks. Even though significantly worse performances occurred when NB was visualized, those differences were not detected between the different types of visualization, supporting the conclusion that single body parts visualization is sufficient to ensure the movement quality. Further tests should be done to test whether the visualization of one body part, no matter if it's task-related or not, is enough to generate the user at least one reference point to her/his body. Despite the positive effects on performance elicited through WB visualization, all tasks are still doable events when NB was visualized during the performances.

The research interest in full-body avatar visualization increased at the current state, and a critical analysis of recent improvements is made (Caserman et al., 2020). This survey summarized the content, including fifty-three publications, and the WB visualization can enhance the sense of embodiment and immersion. Besides, the authors detected a trend to track movements for multiple users simultaneously in real-time and could also be interesting for future sport-related VR applications.

#### 5.3.4 Relevance in the field of sports

During sports, a vast range of motion is necessary to complete the sport-specific demands. In the current study, three different motoric tasks were tested and compared with performances within RW. Generally, the results indicate that balancing, grasping a ball, placing it to a specific area, and throwing a ball into a particular target are doable, even if NB is visualized.

Balancing over the beam can be done with minor restrictions. The participants took longer, and the number of foot strikes increased in VR, which can also be explained due to the higher rate of the subjective estimation of difficulty than in RW. However, the number of errors does not significantly change, suggesting that the task is feasible in VR. Ideas come up immediately to integrate VR in gymnastics, where a sub-discipline is to conduct choreographies consisting of different exercises on the balance beam such as arabesque, various jumps or twists, etc. At this point, it should be emphasized that the present study only covers the basics considering the balancing ability. Further analysis of more complex movements is unavoidable to recommend VR as a training tool also for gymnastics.

However, it could be determined that the visual input of the virtual balance beam was generated successfully by the participants, which leads to the assumption of having a realistic vertical height allowing them to complete even tasks with a higher degree of difficulty. Previous studies also examined the static balance of older adults (Saldana et al., 2017) or dynamic balance using force plates (Robert et al., 2016). Especially in therapy with patients suffering from spinal cord injury, cerebral palsy, and other neurological impairments, VR is used to minimize balance dysfunction and increase motion function (Mao et al., 2014). The authors mentioned that balancing is related to the coordination of the visual, vestibular, and proprioceptive sensation and specifies vital role of the prefrontal cortex for task completion (Bolton et al., 2012). Those neuronal regions provide information about the position and motion of the head and simultaneously using visual cues to modify body posture. A deeper look at the single functions of each system provides information about how VR can be useful in terms of practical involvement in sports.

Basically, the proprioception and somatosensory system collect information of the tactile input and coordinate between limb position and the central nervous system (Mao et al., 2014). The perception and control of the motion and position of the head in a three-dimensional space is realizable through the vestibular system. The weight of the HMD could influence both systems since previous findings confirmed a feeling of fatigue due to higher assessed physical load and may have an impact on participants' performances (Ito et al., 2019). By using visual feedback, the movements can be reorganized and used in a targeted manner (see Figure 4). In the present study, the haptic feedback of the balance beam was constantly provided by tracking the position of a beam in RW in real-time. This is important since practical training always relates to multisensory feedback in real environmental conditions. Keeping in mind that VR should also serve as a method to train sport-motoric tasks at home, it is not clarified whether people can use the adapted VR skills for task completion in RW without getting haptic feedback.

New implementation of hand tracking allows new interaction methods due to multiple input scenarios (Dean et al., 2018). In the throwing task, the participants' performances were influenced by the less visualization of upper body parts such as the hands and arms or the WB. Concerning ball sports in general, previous research focused on improving perceptual-motor skills, which was already implemented in the German Handball Federation (Miles et al., 2014).

New technologies that can track the hands could train dribbling skills without relying on real objects, similar to the current study. Whether and to what extent one's one body needs to be visualized in VR depends on the goal of the training intervention. An additional factor that should be not neglected is the haptic feedback of the ball used in the current study. For example, research has shown that interacting with other players (computer-generalized) in VR is possible even without one's body visualization (Brault et al., 2015). Previous findings also detected higher performances when more information (for example, using a real bat to hit the ball) is given (Ranganathan & Carlton, 2007). The question remains whether the user in VR needs to perceive the haptic feedback to complete the task demands sufficiently. Previous findings show that goalkeepers can intercept the virtual ball without having haptic feedback within VR (Vignais et al., 2015). However, suppose the goal is to compete from home against a real virtual opponent (multiple players within one VE), e.g., during martial arts scenarios or tennis, it is at least necessary to visualize WB in real-time, considering the VR for transferable learning effects. Whether the haptic feedback will lead to increased learning within those sessions should be further examined.

Previous findings show that the fidelity of the VR plays an essential role, and similar performance levels compared to RW dependent on the level of graphical details of the VE (Vignais et al., 2009). The present study shows that with relatively simple graphics and a detailed environment, the user could fully concentrate on the task demands. Already low-level graphics design of the VE could provide a realistic impression and, therefore, can also be used for sport-specific training scenarios. Nevertheless, higher uncertainties occurred in VR, especially in balancing, which raises the question whether this is due to the graphical implementation of the VE. The balancing task is the one with the highest difficulty level than the other tasks described in the current work since balancing over a real beam was necessary to complete the task. It became apparent that the implementation of the object's scale between the two conditions has been successfully illustrated, and the interaction with those was realizable. Even though this was not part of the experiments, the participants could also catch the virtualized ball, which speaks for sufficient tracking in VR also for dynamic objects.

# Chapter 6

## General Discussion

In summary, it can be said that the visual perception in VR differs slightly from that of RW. However, in most cases, these minor differences do not prevent the participants from completing the required tasks. To get a further impression for which tasks this applies, the work is divided into three sections focusing on the ET systems' qualities allowing analyses of gaze behavior, spatial orientation skills, and body visualization. It should be emphasized that not all aspects of the visual perception have been taken up in this work. These are listed in the present chapter, and possible investigations are discussed.

The first section dealt with whether different visual stimuli with different properties (static, dynamic, and static including variable distances) can be fixed in VR as accurately as in RW and whether the measurements are equally precise in both conditions. This is fundamental to consider the combined technic VR and ET for analyses of visual perception within VEs. Basically, it has been shown that the analysis of gaze behavior (in this context consisting of gaze accuracy and precision) and thus the investigations of the visual perception are possible in VR. The gaze accuracy and precision values are comparable to those from RW, which allows the determination of gaze parameters described in 2.2.1. Nevertheless, the quality of ET data should be checked for future applications, as it can have a significant impact on the results, and misinterpretations may creep in. This has further been recognized, and researchers have therefore provided a method that can determine the data quality of an integrated ET system in a simple way (B. Adhanom et al., 2020; Niehorster et al., 2020). This could be important for developing virtual objects that serve as gaze-interactions within VR in terms of their magnitude or size, which can be reliably resolved (Hessels et al., 2016; Hessels et al., 2017). In this regard, further investigations showed existing ET latencies differ in the range of 45 ms to 81 ms within different devices (Fove-0, Varjo VR-1, HTC Vive Pro), which may have an impact on the ability to rapidly adapt visual stimulation in the HMD (Stein et al., 2021).

Besides the remaining differences in the gaze data quality between the devices, this technology has great potential to be also used in sports purposes, which was already used to measure anticipatory skills (Mann et al., 2019). Through the already crystallized advantages in the use of VR, such as being able to represent any form of sporting situation, no real danger for the user, individually adapted level of difficulty, and more realistic scenes, future analyses of gaze behavior, visual perception, and future vision training is more practical using ET in VR. Therefore, this combined technic could be indispensable also for usage in the sports sector. Accordingly, the reactions of visual stimuli or tactics could be trained for any sports. Feints that the opponent initiates could be downplayed to direct the user's attention to the essential body regions that initiative movement. There is an apparent research deficit working with ET in VR during a sport-specific situation, and further investigations could reveal more possible applications fields.

The study also shows that fixating a virtualized object can be equally done within VR compared to RW regarding the visual perceptual performance itself. This is important since previously collected and developed algorithms used in RW can be further considered within VR applications, especially for the distances examined in this study. Unfortunately, this cannot be confirmed for dynamic pursuit eye movements since a higher deviation (measured in degree) is observable within the VR, although the pace of the visual stimuli was the same in both conditions. Nevertheless, it would be fatal to claim that this merely due to the work processes within the visual perception. Supposing the intention is to track moving targets with the eyes (for example, moving teammates or opponents), the implementation should be completed directly (for example, programming trajectory movements) instead of using integrated videos since the sampling rate might be reduced. Furthermore, the recording frequency should also be considered since the currently used ET system deviated slightly from the manufacturer's specifications, which may impact the gaze analysis of fast movements.

One of the not examined factors of the visual perception is PV. The most common VR devices on the market today show a limitation in the FoV, which leads to a loss of information, especially during sports. For adults, the horizontal extent of the binocular visual field is approximately 214° (± 107° on each side) (Strasburger, 2020), and the vertical 60°-70° up and 70°-80° down (Axenfeld & Pau, 1980). Here, especially the loss within the horizontal axis arises, as most applications are limited to 110 degrees, although there are already plans for HMDs that will allow a natural FoV[11]. This should not be disregarded since Vater et al. (2020) emphasized the importance of PV concerning sports-related situations. In addition, some of the users complain about the sharpness in VR. Therefore, some products offer to adjust the IPD or even the individual visual acuity of the user (e.g., SteamVR Valve Index[12]). This ensures

[11] StarVR from the Swedish company Starbreeze: https://mixed.de/starvr-vr-brille-mit-einem-sichtfeld-von-210-grad/
[12] https://store.steampowered.com/sub/354231/

improved usability and could further minimize the differences to RW realizing realistic-looking sports scenarios in VR.

Thinking on the usage of VR for sport-related purposes, the active execution of movements should not be missed. In the first section, the participants were placed in a fixed position being not able to move. The other studies that are part of the second and third sections included actively walking for task completion. Therefore, section 2 and section 3 provide a better imagination of possible movement completion in VR. In the second section, the main questions were whether distances could be estimated equally in VR compared to RW, routes can be run off with the same precision, and whether static objects can be similarly approached and remembered in both conditions. Generally, no significant differences could be found within spatial orientation ability, such as distance estimations, route recreations, and actively walking. Even balancing over a beam, pick up a ball and place it into a specific area and throwing it into a virtualized target can be done, however, with few restrictions. Those restrictions are found in more time needed for balancing and grasping tasks, and almost all tasks are rated more difficult in VR. Hereby, the third section has shown that it is unnecessary to visualize the WB, which is in line with previous findings (Lugrin et al., 2018). During the rotation and pathway task, the observation of the VE was also done without having visual feedback of body parts, and actively walking to static objects could be equally performed, which is in line with previous findings (Kim et al., 2019). Nevertheless, it can be seen from the results of the motoric task completion that at least one reference point of one's body should be visible (at least for younger adults) since the performance minimal decreases when no visualization of any body part was provided. This is a crucial finding since this makes it more practical for application by using the system integrated controller as a reference point for the arms or hands, allowing to get additional feedback. Those controllers can also track finger movements, which could lead to natural hand movements, and therefore, higher immersion and increased identification with the virtual avatar's movements (body ownership) occur. To this end, further systems are being developed which will detect stances, positions, movements, forces, etc., of at least one body part allowing the user to control a master (avatar). The increased development of future applications is significant for sports science. For example, Dr. Marcel Reese (University of Bielefeld) works on integrating exoskeletons into VR, allowing the pure visualization of a virtual avatar and physical resistors (strength and balance feedback) and natural movements, which could be helpful in the sports field. For example, perceiving visual stimulated environments on the one side and physical resistance on the other could elicit physiological adaptations leading to a training intervention comparable to RW.

Regarding this, previous research shows more benefits that could appear. Multisensory feedback improves embodiment, which increases the sense of presence, and therefore, higher performances can be expected. However, VR should also be intended to support motor learning as it was done previously (Hülsmann et al., 2018). The conduction of motoric tasks does not require the full body vision within VR as long as the movements are simple for participants like the chosen motoric tasks in this work. The question is whether this also applies when the user needs to learn a new movement since feedback (especially visual, auditory and haptic) is essential for learning processes (Nojima et al., 2013; Sigrist et al., 2013). Here, there are doubts whether possible transfer effects to RW will show up when the WB visualization is waived due to the lack of embodiment (Haar et al., 2021).

Natural walking techniques could significantly impact immersion and provide correct proprioceptive/kinesthetic feedback (Nilsson et al., 2018). Allowing to walk naturally within VEs without physical space limitations requires expensive and cumbersome hardware components such as omnidirectional treadmills. Alternatives are further developed without additional hardware components complicating the access and raising costs. This can be assured of the described possibilities in the first section by involving ET systems and using the user's gaze to determine saccadic movements facilitating the infinite walking method. The integrated ET systems also allow the analyses of visual perception in general vision training by presenting visual stimuli, different kinds of sports situations from the 1PP, ensuring a high degree of realism which could also be used for tactic training. Hereby, the second section results reveal equal processing of the visual input between real and virtual environments, at least for static objects/items for distance estimation from an egocentric perspective, depth perception, and spatial arrangement. As far as the size of the physical space and the tracking area of the VR system is sufficient, training can also be done within this area. Nevertheless, interaction on a larger field (HTC Vive Pro equipped with four lighthouses offers a space of 100 square meters) is unrealistic with today's means. For example, reproducing a scene on a soccer field, movements are only possible on a limited area using natural walking techniques. This has to be considered for the sports-specific development of virtual training scenarios.

Another critical component of VR training will be its duration. All tasks in VR required a maximum of 20 minutes since previous studies found an increased risk of CS symptoms spending too much time in VR, at least for older adults (Petri et al., 2020). The authors found no impact between 10 minutes and 20 minutes exposure time on cybersickness and occurred symptoms after 10 minutes remained relatively stable. To examine possible CS symptoms or make sure that the participants are doing well, self-created and already established questionnaires (SSQ) were handed out to the participants to get an impression of possible obstacles during VR experiences and the usage in sports. Although high values of the SSQ appeared that represent high CS risk, the participants never complained about factors such as disorientation, nausea, or oculomotor. New findings report that SSQ seems to be not applicable for measuring cybersickness in commercial HMD VR due to the psychometrics qualities (Sevinc & Berkman, 2020). How long a participant feels comfortable within a VR training or learning session, additional use of biofeedback such as heart rate (Preciado et al., 2021), blood pressure, electrogastrogram (EGG), skin temperature, and electroencephalograms (EEGs) (Rebenitsch & Owen, 2016) could be helpful to reveal the appearance of CS symptoms more valid.

One further aspect should not be ignored in future VR applications. Sport is not only about bringing one's performance to the optimum; the social component is also an important part (Bum et al., 2018). Today's technology even makes it possible for several users to be in one VE and interact together. This can provide increased motivation and affect the joint training of a technique, in which one can exchange information with other athletes in a three-dimensional computer-generated environment from home. For example, Bum et al. (2018) showed that although men and women differ in their choice of sports, they do enjoy the same types of VR sports.

It can be seen as a new possibility for developing training scenarios within a VE, keeping in mind to gain movement improvement included transferring skills into real conditions. Although the present work does not directly assess athletic performance except in the third section, the other included studies (first and second section) contain the evaluation of skills that indirectly play a major role during motoric task completion. Since basic tasks can be equally performed within VR compared to RW, the use of VR can be advocated. Nevertheless, only basic skills were tested in this work, whereas sports offer much more complex situations.

To propose VR for sport-related use, it is essential that the user behave the same way in virtual and real environments and that their perception and action are coherent (Faure et al., 2020). The results of this work motivate to research sport-specific applications since basic skills are doable, and VR offers many opportunities to establish new forms of training, improve or learn sports-specific skills, analyze athletic levels, such as visual perception or reaction times, and increase motivation by shifting the attention away from physical pain. Overall, the stimulation of the visual cues in VR can be done at least to the acceptable level and resulting actions could be performed comparably to those from RW.

# Chapter 7

## Conclusion and Outlook

The present work has already shown that various movements requiring basic skills can be reliably completed in VR. Accordingly, new ideas emerging to consider VR as a tool to enable independent training for home use. Hereby, the ideology of not deviating from traditional training plays a decisive role. VR could serve as additional training using natural movement executions and not teleport-locomotion techniques realized through new implementations. To use VR for skill acquisition or learning tool, further studies would have to conduct training interventions, as the previous controversial results came out in favor of or against VR training regarding its effectiveness and efficiency. For performing basic motor skills, it is not essential to visualize the whole body in VR. However, since VR can be particularly effective for learning new movements, further studies need to follow to verify whether the whole body or only a part of it needs to be visualized for learning new skills. What can be said in any case, based on the results of this work, is that at least one part of the body (usually task-specific) that has an absolute reference point must be visualized to approximate the performance from the real world.

The focus of the current work relies on analyzing the visual perception and its comparison to those from RW, although other senses can be stimulated within the VR. Multisensory stimulation has positive effects on the degree of reality and provides a higher immersion. Further investigations may reveal the need for multiple stimulated senses to increase the VR experience and support learning or training within VE. Since the stimulation of haptics is relatively rare than the others (due to non-existing technology) but essential for many sports disciplines, further studies could shed light on a solution to circumvent this problem.

Due to its high flexibility and development of a pre-programmed sequence of individual conceptualized training scenarios, it can be a helpful tool for autonomous or self-guided training. This has not yet been tested sufficiently at the current state but has great potential for already feasible movements.

This work has presented the potential of VR in many applications and advocates the usage in certain sports areas. It also shows future realizable implementations, which will further expand the applications due to more practical equipment, usability, and the increasing demand decreasing the costs of VR systems for private use.

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**Statutory declaration**

(Ehrenerklärung)

Ich versichere hiermit, dass ich die vorliegende Arbeit ohne zulässige Hilfe Dritter und ohne Benutzung anderer als der angegebenen Hilfsmittel angefertigt habe.

Verwendete fremde und eigene Quellen sind als solche kenntlich gemacht.

Ich habe nicht die Hilfe eines kommerziellen Promotionsberaters in Anspruch genommen. Ich habe insbesondere nicht wissentlich:

- Ergebnisse erfunden oder widersprüchliche Ergebnisse verschwiegen
- Statistische Verfahren absichtlich missbraucht, um Daten in wissenschaftlich ungerechtfertigter Weise zu interpretieren
- Fremde Ergebnisse oder Veröffentlichungen plagiiert
- Fremde Forschungsergebnisse verzerrt wiedergegeben.

Mir ist bekannt, dass Verstöße gegen das Urheberrecht Unterlassungs- und Schadensersatzansprüche des Urhebers sowie eine strafrechtliche Ahndung durch die Strafverfolgungsbehörden begründen können.

Die Arbeit wurde bisher weder im Inland noch im Ausland in gleicher oder ähnlicher Form als Dissertation eingereicht und ist als Ganzes auch noch nicht veröffentlicht.

Ich erkläre mich damit einverstanden, dass die Dissertation ggf. mit Mitteln der elektronischen Datenverarbeitung auf Plagiate überprüft werden kann.

Magdeburg,

_________________________

Stefan Pastel

**Appendix A (Publications 1-4)**

**A.1** Comparison of gaze accuracy and precision in real-world and virtual reality

**Conceptualization:** Stefan Pastel, Chien-Hsi Chen, Katharina Petri, Kerstin Witte

**Data curation:** Stefan Pastel

**Formal analysis:** Stefan Pastel

**Investigation:** Luca Martin, Mats Naujoks, Stefan Pastel

**Methodology:** Stefan Pastel, Chien-Hsi Chen, Katharina Petri, Kerstin Witte

**Project administration:** Kerstin Witte

**Software:** Chien-Hsi Chen, Mats Naujoks, Stefan Pastel

**Supervision:** Stefan Pastel, Katharina Petri, Kerstin Witte

**Validation:** Stefan Pastel, Chien-Hsi Chen, Katharina Petri, Kerstin Witte

**Visualization:** Stefan Pastel, Chien-Hsi Chen

**Writing – original draft:** Stefan Pastel, Chien-Hsi Chen

**Writing – review and editing:** Stefan Pastel, Kerstin Witte

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ORIGINAL ARTICLE

# Comparison of gaze accuracy and precision in real-world and virtual reality

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## Abstract
Virtual reality (VR) is popular across many fields and is increasingly used in sports as a training tool. The reason, therefore, is recently improved display technologies, more powerful computation capacity, and lower costs of head-mounted displays for VR. As in the real-world (R), visual effects are the most important stimulus provided by VR. However, it has not been demonstrated whether the gaze behavior would achieve the same level in VR as in R. This information will be important for the development of applications or software in VR. Therefore, several tasks were designed to analyze the gaze accuracy and gaze precision using eye-tracking devices in R and VR. 21 participants conducted three eye-movement tasks in sequence: gaze at static targets, tracking a moving target, and gaze at targets at different distances. To analyze the data, an averaged distance with root mean square was calculated between the coordinates of each target and the recorded gaze points for each task. In gaze accuracy, the results showed no significant differences between R and VR in gaze at static targets (1 m distance, $p > 0.05$) and small significant differences at targets placed at different distances ($p < 0.05$), as well as large differences in tracking the moving target ($p < 0.05$). The precision in VR is significantly worse compared to R in all tasks with static gaze targets ($p < 0.05$). On the whole, this study gives a first insight into comparing foveal vision, especially gaze accuracy and precision between R and VR, and can, therefore, serve as a reference for the development of VR applications in the future.

**Keywords** Eye-tracking · Virtual reality · Gaze behavior · Head-mounted display · Accuracy · Precision

## 1 Introduction

Virtual reality (VR) is one of the fast-growing technologies that has many potential applications involving a huge amount of visual cues that are important when analyzing gaze behavior. Currently, the most frequently used VR technology in the field of entertaining or for educational purposes is HMD. The current versions of HMDs have a high-resolution display and are combined with a motion tracking system to ensure high quality of immersion and user experience. Moreover, VR has many advantages, such as the development of highly customizable virtual training scenes, affordable cost of the system, and high accessibility in a most domestic environments (Düking et al. 2018; Neumann et al. 2018). Moreover, VR can simulate or reproduce images and scenes that are difficult to perform in a real-world scenario. These features make VR an ideal tool for training in different fields, such as rehabilitation (Rose et al. 2005; Duque et al. 2013), health sports (Molina et al. 2014), as well as recreational sports and high-performance sports (Petri et al. 2018a, b).

In addition to the application in healthcare, some studies in the field of sport also showed an improvement after the training sessions using VR, such as in karate (Petri et al. 2019), throwing dart (Tirp et al. 2015), and baseball batting (Gray 2017). All these sports require a continuous focus on the target. For example, a dart player needs to focus on the targets from a fixed distance. In this case, the depth perception and the sharpness of the targets in VR become highly relevant to the results. However, these studies did not provide further information regarding gaze accuracy and precision in the comparison between real-world (R) and VR. Accuracy and precision are considered the most important

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parameters for data quality of eye movements (Ooms et al. 2015).

The visual system allows the extraction of valuable information from the environment to complete highly skilled actions. In sporting activities, it is essential to perceive teammates, opponents, one's position, or properties concerning one's surroundings (size, target, etc.). Unfortunately, the foveal vision is restricted to 1°–2° in the field of view (FOV), which leads to constant eye movements to see sharply and extract detailed information (Vater et al. 2017). Gaze accuracy is defined by the degree of visual angle within this FOV (Krokos et al. 2019). It plays an essential role in examining the interindividual differences in attention span and identifying the key points during observation while learning a new movement. Holmqvist et al. (2015) describe gaze accuracy as the averaged deviation between the position of a considered point (target stimulus) and the position captured by the eye-tracking system (point of regard). Precision is defined as the ability to reliably reproduce a measurement given a fixating eye (Nyström et al. 2013). While accuracy defines the distance between true and recorded gaze direction, precision refers to how consistent calculated gaze points are, when true gaze direction is constant (Holmqvist et al. 2012). When we consider using VR as a training tool for sports, the user should ideally have almost the same experiences in perception as he would have in real conditions. Furthermore, due to the progress of technical devices, it is possible to have light eye-tracking systems in VR headsets (Clay et al. 2019). Therefore, it is essential to investigate in depth the specific differences between R and VR regarding gaze behavior.

The goal of the current study is to examine whether gaze accuracy and precision in a simulated virtual scenario are comparable to those of the real environmental setup within different gaze tasks.

## 2 Related work

With eye-tracking systems, the accuracy of a target stimulus can be determined by specifying angular deviations. Many manufacturers specify a deviation of < 0.5° in their measurement systems (Feit et al. 2017; Nyström et al. 2013). Higher accuracies are found in the center of FOV because the pupils are the largest detected object in size by the integrated eye-tracking cameras when the target is centered in front of the eye-tracking system (Hornof and Halverson 2002).

On the other hand, the level of accuracy is not the only data quality issue affecting the viability of research results. There are many influencing factors, which can result from either technical or non-technical issues, such as the homogeneity of the testing participants (Blignaut and Wium 2013). Another study showed more factors that might have an impact such as different calibration methods, the individual characteristics of the human eye, the recording time as well as the gaze direction. Additionally, the operator's experience can also affect gaze data such as accuracy and precision (Nyström et al. 2013). Participant-controlled calibration is predestined for better accuracy and precision. This study has also demonstrated that contact lenses, downward-pointing eyelashes, and smaller pupil sizes harm gaze accuracy. Further studies have figured out that the measurement method and different calculations of gaze accuracy in R also have an influence on gaze accuracy (Feit et al. 2017; Holmqvist et al. 2015; Hooge et al. 2018; Nyström et al. 2013). Moreover, also different environments and different measurement systems can have an affect (Feit et al. 2017). Accuracy is a prerequisite for several technological devices. For example, gaze-based communication technologies, where dwell time selection is a common method for interacting with options on a computer-based surface, require high accuracy, too. Studies analyzing the selected target by using the gaze position for physical interactions (e.g. Pfeuffer et al. 2017) showed how important gaze accuracy is in VR.

When classifying the event detections to define fixations or saccades, another important gaze parameter must be considered: precision. Nyström et al. (2013) tested precision with different systems, resulting in values of 0.01° to 0.05° for tower-mounted systems and 0.03°–1.03° for remote ones. For instance, a high precision must be given when comparing the number of fixations or the fixation area in R with VR. However, no such comparisons exist up to now.

It needs to be considered, that the representation of the environment in VR takes place via an artificial way. In order to evoke a high presence in the virtual world, the VR system has to manipulate the human perception (Dörner et al. 2013). Possible reasons that have an influence on the performances in VR can result from a distortion of the environment, the perceived depth information, or the level of fidelity. To implement sports training in the VR, it is of great importance to figure out how accurately and precisely the participants perceive short appearing stimuli in fixed and movable conditions. In general, previous investigations aimed to compare different VR applications with each other (Krokos et al. 2019). Clay et al. (2019) have described the technical and practical aspects of eye-tracking in VR and gave an overview of different software and hardware solutions. However, a comparison between VR and R regarding gaze behavior has rarely been made. This study's aim is therefore to examine the differences of gaze accuracy and precision between R and VR under controlled testing conditions.

The main goal of this study is to investigate how gaze accuracy and precision would be affected by different kinds of visual stimuli and scenarios (R vs. VR). Since the resolution in VR is significantly lower than the one of the human eyes and latencies can occur, we assume that differences occur between the gaze accuracy and precision in R and

VR. The three-dimensional world that is shown in VR on a display can lead to differences in distance perception (Loomis and Knapp 2003; Messing and Durgin 2005; Renner et al. 2013). Clay et al. (2019) also mentioned the disparity between vergence and focus, since the distance to the display remains the same and therefore eye strain and fatigue can occur. While we use an older VR application (HTC Vive) in this study, we have to consider all these mentioned limitations, since those components may have an impact on gaze measurements. To avoid possible differences by using devices including different technologies (e.g. manufacturer, measurement method via corneal reflection, use of the same algorithms), the older HMD was chosen to have comparable values between the real and virtual measuring technology (see chapter hardware).

# 3 Methods

To compare gaze accuracy and precision between R and VR, three tasks were designed: (1) static stimuli appearing at four different positions, (2) a stimulus moving across the screen in the form of an infinity loop, and (3) static stimulus presented at different distances in the center of the screen. We have included those due to the confrontation of different stimuli in daily life. All tasks are performed in R and in VR to have comparable results regarding gaze behavior. The experimental setup, protocols, and data analysis are described in the following subsections (see Fig. 3).

## 3.1 Participants

Twenty-three young sports students (ten females, eleven males) with an average age of 22.6 ± 3.02 were recruited for this study. However, the data recording of two participants was rejected due to a lack of quality and technical problems during the conduction. All participants took part in three tasks which will be presented later. The participants' previous experiences in VR and in eye-tracking studies were noted. The participants were asked whether they had ever taken part in a VR or eye-tracking study, or if they owned VR applications themselves. Six participants stated that they had already gained VR experience, but none of them owned a VR application. Five participants had already participated in eye-tracking studies. Furthermore, related gaming experiences including the type of games and the frequency of gameplay were also noted. Eleven participants regularly played video games ($M = 4.58$ h per week, $SD = 2.51$). For vision correction, only participants using contact lenses (8 participants were affected) were allowed, because it was not possible to wear the HMD and glasses simultaneously. All participants received the instructions prior to the study and gave their written consent. The study was approved by the authors 'university's ethics committee.

## 3.2 Experimental setup

### 3.2.1 Hardware

The experimental setup is shown in Fig. 1. The participants were seated in front of a table. A chin rest was used to support the participant's chin in a comfortable posture. The participant's head was also fixed during the experiment (Clemotte et al. 2014; Reichert 2019). The height of the center point of the monitor was adjusted to the eye level of each participant (Ooms et al. 2015).

In the real-world testing condition, binocular Eye Tracking Glasses 2.0 (SensoMotoric Instruments, Germany) with a resolution of 1280 × 960 pixels and the sampling frequency of 60 Hz was used to track the eye movement. A laptop (Lenovo, China) was used to record the eye-tracking data. A 23.5-inch monitor with the resolution of 1920 × 1080 pixel and 60 Hz refreshing rate (EIZO ColorEdge CG248, Japan) was used to display instructions for the experiment. In this study, the optimal visual acuity distance (between the participant and the monitor) of 1 m was chosen. The distance ensured that the participants could achieve a complete view of the monitor without head movements.

The setup in the VR was the same as in the real-world condition. An HTC Vive HMD (HTC, Taiwan) with an integrated eye-tracking system (Sensorimotor Instrument, SMI, Germany; resolution: 2160 × 1200 pixels; frequency: 90 Hz; 110° field of view) was used to display the virtual environment. The approximate resolution of the screen that is rendered in VR condition was 720 × 400 pixels. This VR setup ran on a computer with Intel(R) Core(TM) i7-7700 CPU @ 3.60 GHz, 16 GB RAM, and an NVIDIA GTX 1080 graphics card. The manufacturer specifies a gaze accuracy of 0.4°–0.5° (SensoMotoric Instruments 2016) overall distances and guarantees parallax compensation (iViewETG User Guide Version 2.7 2016). The precision values were not provided for the mobile system. For the SMI RED 250, which also used the corneal reflection method, a precision of 0.03° is mentioned by the manufacturer (SensoMotoric Instruments 2016).

The following data were recorded by the eye-tracking software: interpupillary distance (IPD), the points of regard of the individual eyes (POR), and the gaze direction vectors of both eyes (Fig. 2).

The stimuli were presented via a PowerPoint presentation, ensuring the same chronological sequence for all participants. Studies have shown that too bright background light can affect gaze accuracy negatively (Drewes et al. 2011). In the current study, we therefore chose a gray screen background. The fixation cross (in the middle

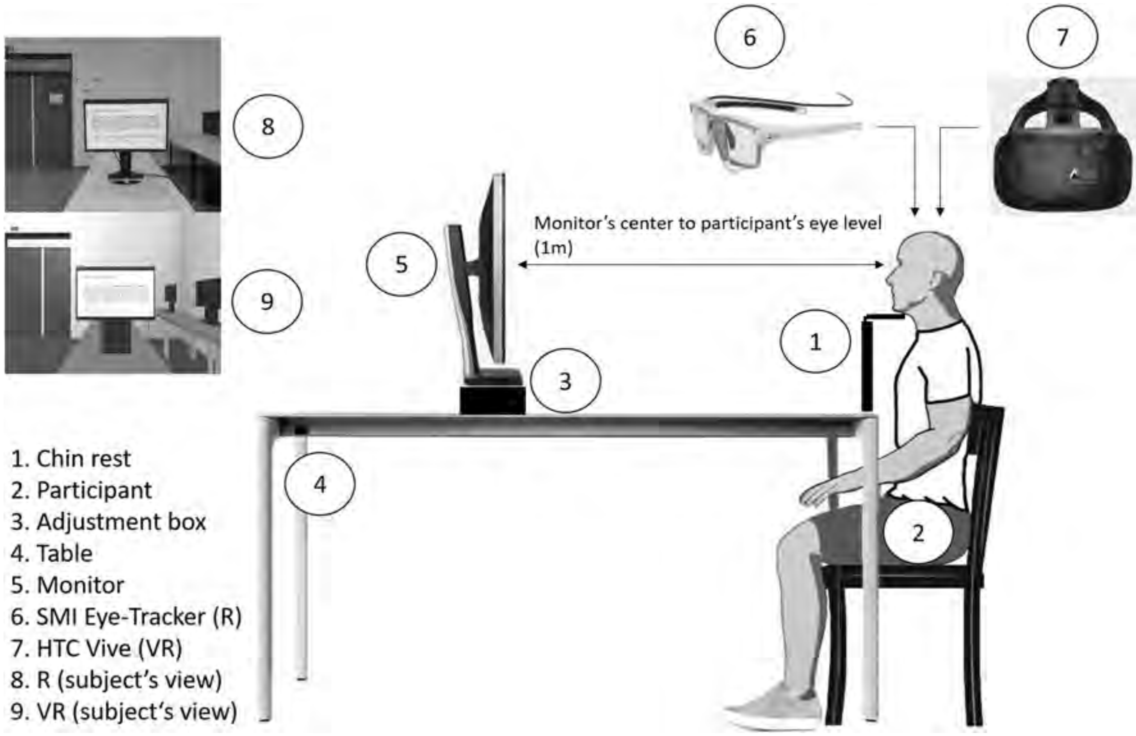


**Fig. 1** Overview of the experimental setup

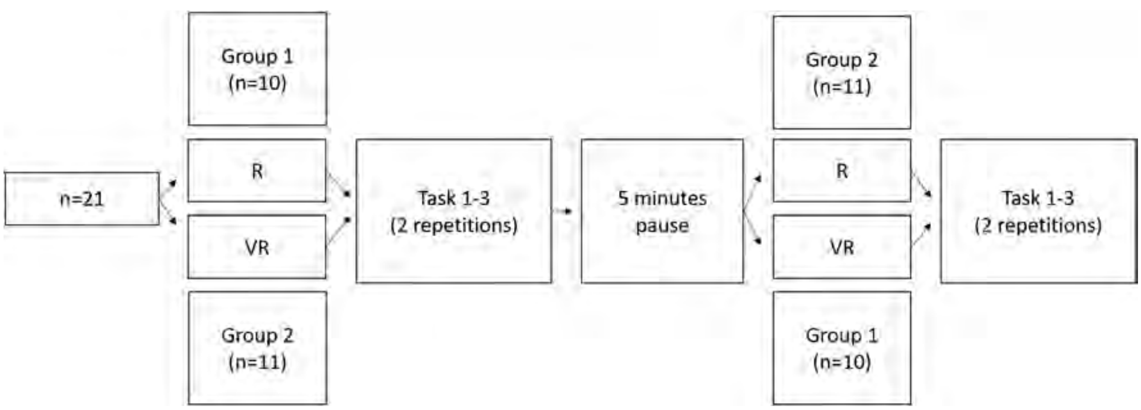


**Fig. 2** Overview of the experimental conduction. Each task was performed twice in R and VR. The participants had to complete all tasks in both conditions. For detailed information on tasks 1–3, see Fig. 3

of the screen) and the stimuli at the corners were 15.64° (FOV) apart. The presented crosses for task 1 were 2 cm wide and 2.5 cm high (0.99° horizontal and 1° vertical on the FOV), the diameter of the dot in task 2 was 1 cm (0.57° on the FOV), and the cross in task 3 was 8 cm wide and high (the cross in the middle of the white one was 1 cm wide and high, again 0.57° on the FOV, see Fig. 3 Task 3). The presentation of the visual stimuli was the same in both conditions. For further information see also Fig. 4.

#### 3.2.2 Software

For data recording and extraction in R, the iViewETG 2.7 and BeGaze 3.6 (SensoMotoric Instruments, Germany, 2009) were used. The VR environment was created within

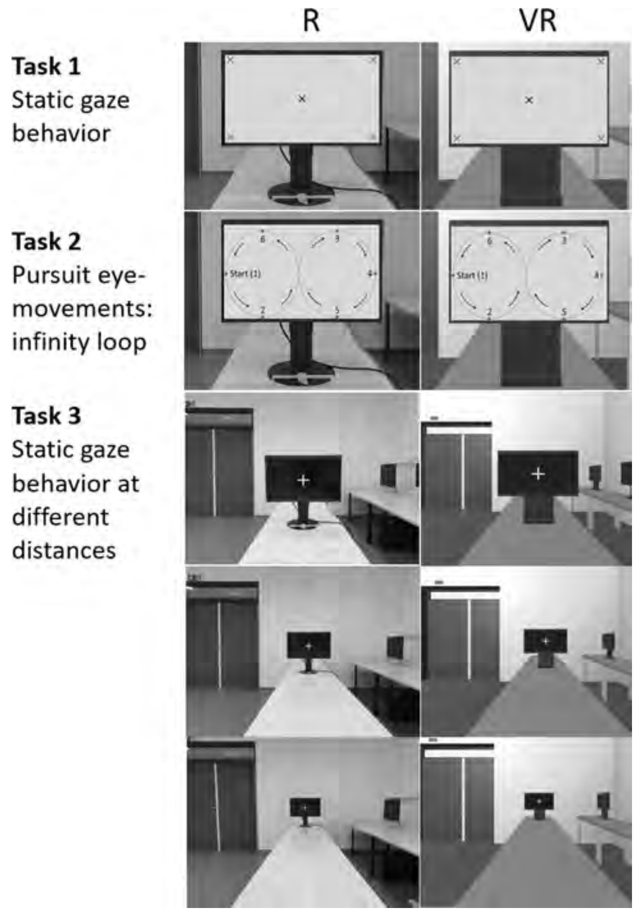


**Fig. 3** Overview of all tasks from the participant's perspective. R: reality. VR: virtual reality

Unity 2018.3 (Unity Technologies, U.S.A.), and the data was accessible through the official plugin provided by SMI (iViewNG HMD Api Unity Wrapper v1.1, 2017).

### 3.3 Experimental protocol

The participants were randomly assigned into two groups: group 1 started the experiment in VR and group 2 began in R-condition. After installing the hardware components, the calibration was performed and the tasks were carried out in their predefined order (see Fig. 3). Each participant had to do each task twice. After completing each task per condition, the participant could relax and read the instructions for the next task. Subsequently, the participants changed the conditions (R/VR). After the participants completed all tasks, they were asked to complete a feedback questionnaire. The whole experiment took around 30 min per participant.

#### 3.3.1 Preparation

In R, the height of the center of the monitor was adjusted to the participant's eye level in the seated position. The participant was fitted with the mobile eye tracker, which was firmly fixated on the participant's head. To gain reliably eye-tracking data from the HMD, it was important to adjust the individual interpupillary distance for each participant (Dörner et al. 2013). The HMD was placed on the head of the participants and they could then adjust the pupil distance themselves until they had a clear view. The participants were seated in front of a table, which was the same in R and VR ensuring equal haptic feedback in both conditions. The preparation was identical for each task.

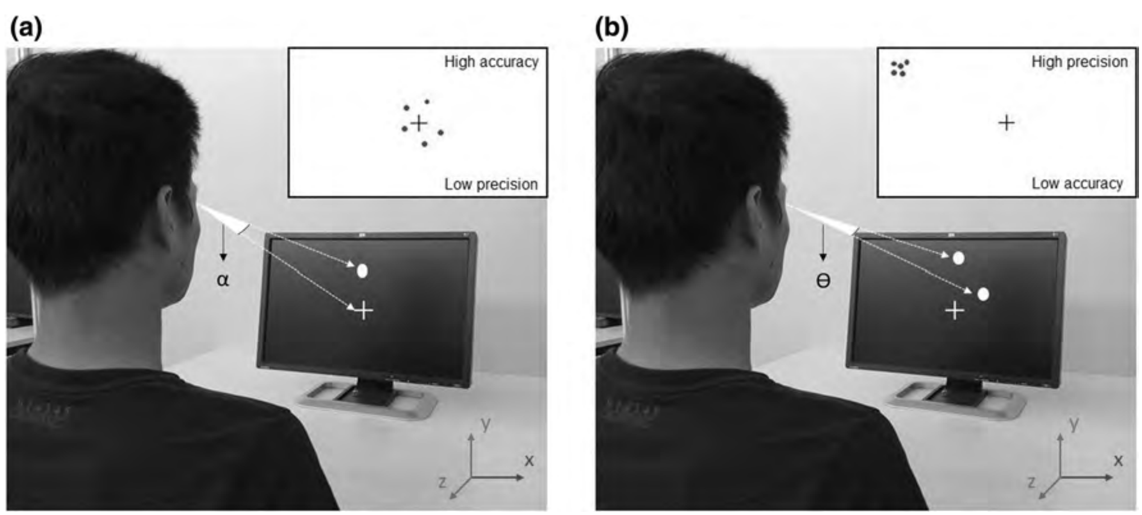


**Fig. 4** Overview of gaze accuracy (**a**) and gaze precision (**b**) based on Nyström et al. (2013). The dots indicate the point of regard (POR) and the crosses indicate the target stimulus. The white boxes provide an example for **a** high accuracy but low precision and **b** high precision and low accuracy. The arrows indicate the angle for each parameter. For better representation, exaggerated values for accuracy and precision have been used. Below on the right is the coordinate system, which was used for the calculation of the deviating angles

#### 3.3.2 Calibration

A 3-point calibration was conducted for both devices according to the manufacturer's calibration protocol. The HMD was installed on the participant's head to be in the best position for the eye-tracking recommended by the manufacturer. Before each recording or trial, the calibration was repeated to avoid a loss of data quality over time due to a reduced shifting of the measurement system. The preparation and calibration procedures were identical in all three tasks.

### 3.4 Parameters

The algorithms calculating the accuracy and precision of the different measuring systems are based on raw data. In Fig. 4, both parameters are visualized. Gaze accuracy can be explained by the averaged distances between the position of the participants' gaze point and the target stimuli (gaze accuracy). The precision values indicate an averaged distance between each gaze point made by the participant. Accordingly, high accuracy and precision are characterized by low values. Meaning, the lower the angle between the two vectors (a) $\alpha$ for gaze accuracy and (b) $\theta$ for precision (see Fig. 4), the smaller the gaze deviation, and hence the higher the gaze accuracy and precision.

#### 3.4.1 Accuracy (offset)

According to Holmqvist et al. (2015), the same formulas were used to calculate the average accuracy of the participants over the angle distribution ($\alpha$) (see Fig. 4). The accuracy $\alpha_{Offset}$ results from the mean value, which corresponds to the recording frequency of the eye-tracking systems, and the mean value of all calculated angular deviations.

#### 3.4.2 Precision (root mean square)

The same procedure or formula was used for the precision, instead, here the deviation of the distance was not determined from the reference cross (stimuli) to the (made) point of regard (POR), but the chronological sequence of the PORs recognized by the system. By using the root-mean-square (RMS), the quadratic mean was obtained, which in turn was calculated in deviation of the degree (Holmqvist et al 2015). The angle calculation is also used to extract the precision of the eye-tracking system. This is determined by the angle between two successive positions of the pupil cross (Holmqvist et al. 2015). $\theta$ represents the angle between the two vectors of each made gaze point (see Fig. 4). The squares of all angle values calculated in a POR (of a cross) were summed up and divided by the number of data samples for the quadratic mean value.

#### 3.4.3 Algorithm for accuracy and precision

To calculate the angles of accuracy and precision, we assume that the position of the participant's eyes was fixed in space, and the distance between the eyes and the monitor was constant. Through this, we could create an abstract coordinate system with the origin being the central point of the monitor. The *X*-axis was in the horizontal direction, the *Y*-axis was in the vertical direction, and the *Z*-axis pointed towards the participant (see Fig. 4). Therefore, the coordinate of the participant's eyes can be defined as point *P* (0, 0, 100), because they were seated 100 cm in front of the screen. The next step was to calculate the angle between the eyes and the targets for the two parameters mentioned above. Therefore, we converted all the coordinates of the PORs and the relevant targets from pixels to centimeters. Then, the vectors from the eyes to the targets and the vectors from the eyes to the PORs were obtained. With these vectors, the dot product was used to calculate the angle accuracy using the formula shown below. The same idea was implemented for precision with a slight modification of the input vectors. For precision, the vectors from the eye position to each POR were calculated as well as the angles between each vector over time.

### 3.5 Data processing

To calculate the deviation of the system's registered gaze to the target (accuracy) and the deviations of the PORs among themselves (precision), the following steps were applied. When extracting the data, we were able to use the eye tracker's coordinate systems provided by the measuring systems. The origin of the 2D image of the two systems was defined at the top left corner. For each trial, the coordinates of the target stimuli as well as the point of regards (POR) were determined. The different pixels within the horizontal (*X*-axis) and vertical (*Y*-axis) direction were calculated by using the Pythagorean theorem to determine the size of the direction vector between them. Thus, we calculated the Euclidean distance from each POR to the target stimulus. All PORs were recorded and evaluated within an area of interest (AOI, in the form of a circle with a circumference of 3°). This ensured to avoid influences on gaze accuracy and precision by measuring those PORs, which were recorded between the reference cross and the target stimuli. To compare our results with results of other studies, the calculation of the deviations in angles for both, accuracy and precision, was conducted by using the previously mentioned vector calculation.

The statistical evaluation was performed with IBM SPSS Statistics 25. The algorithms for calculating the angular deviations were implemented in MATLAB 2018b (The MathWorks, U.S.A.). In total, the data sets of 21 participants were available for statistical analysis. The verification of significant differences was performed above an alpha level of 0.05. Pearson's correlations coefficient ($r$) were used to indicate the effect sizes.

### 3.6 Task description

#### 3.6.1 Task 1: Static gaze behavior

**3.6.1.1 Conduction** Instead of using concentric circles as stimuli (Clemotte et al. 2014), we used crosses in the current study (see Fig. 3). A cross in the center of the screen was used as a reference to the other crosses. The other crosses appeared at the corners of the screen for 1.8 s. We wanted to record the gaze data for each cross for at least one second, so we added 0.8 s. The idea was to analyze whether participants were able to see fast emerging stimuli in VR. Each cross was displayed four times in a randomized order so that the participants could not predict where to look next. The reference cross remained visible at all times. The participants were instructed to fixate the middle cross as the new starting position after each fixation of one of the crosses at the corners was made. Each cross was presented for 7.2 s, bearing in mind that the reaction time must be subtracted from the participant's observation. The participants were asked to make as few blinks as possible when the stimulus targets appeared to ensure good data quality and to reduce problematic data collection.

**3.6.1.2 Data analysis** The univariate ANOVA with repeated measures for two paired samples and $t$ test comparisons with calculated effect sizes were used to analyze differences in the gaze accuracy for each positioned cross [top right, bottom right, top left, bottom left]. For precision, a nonparametric Friedmann test of differences and Bonferroni-corrected post hoc comparisons with calculated effect sizes were conducted to analyze possible differences between each positioned cross.

### 3.7 Task 2: Pursuit eye-movements

#### 3.7.1 Conduction

In this task, a dot appeared on the monitor (left side). This dot moved across the monitor in the form of an infinity loop for 15 s. The participants had to follow it with their eyes until the blue dot returned to the origin of the movement trajectory and stopped moving.

**3.7.1.1 Data analysis** A nonparametric Friedman test of differences and Bonferroni-corrected post hoc comparisons with calculated effect sizes were performed to analyze possible significant differences of gaze accuracy for each reference point (see Fig. 3). The center was not taken into account in the analysis, because gaze accuracy and precision were already examined in the other tasks.

### 3.8 Task 3: Static gaze behavior at different distances

#### 3.8.1 Conduction

In the third task, a white cross appeared on a black background. Inside the white cross, a small black cross was visible so that the participants would not have any difficulty in discovering the center of the cross, especially for the 1 m distance. For each distance, the participant should fixate the cross for 3 s to ensure that they did not stare at the same target for too long and lose concentration in the process. After the fixation was finished, the monitor was set to the next distance (1 m, 2 m, and 3 m). Afterward, the monitor was repositioned and a new calibration was carried out.

**3.8.1.1 Data analysis** In the third task, a nonparametric Friedman test and Bonferroni-corrected post hoc comparisons with calculated effect sizes were also applied due to a lack of normal distribution. The gaze accuracy and precision for all distances [1 m, 2 m, 3 m] between both conditions [VR, R] were compared.

## 4 Results

### 4.1 Task 1: Static gaze behavior

Table 1 shows the results with no significant differences regarding gaze accuracy in task 1. It shows the basic level of information required in order to assess eye movement research (Holmqvist et al. 2012). In R, most participants fixated the top right (TR) and in VR the top left (TL) accurately concerning the different directions. For both measuring systems, the lowest accuracy was achieved at the low crosses, which was bottom left in R and the bottom right in VR.

The data across the different positioned stimuli were checked for normal distribution (Kolmogorov–Smirnov, $p = 0.200$). The Levene test showed equal variances ($p = 0.121$). A one-way ANOVA was conducted to compare the effect of the position of the cross (top left, top right, bottom left, bottom right) on the gaze accuracy (deg) between VR and R conditions. An analysis of variance showed no significant differences between the differently positioned crosses (top left, top right, bottom left, bottom right) in

**Table 1** Comparison of the gaze accuracy and precision between R and VR for each positioned cross

| Cross position | R $M \pm SD$ (deg) | VR $M \pm SD$ (deg) | $z$ values, significance | Effect size ($r$) |
|---|---|---|---|---|
| *Accuracy* | | | | |
| TR | $0.46 \pm 0.25$ | $0.44 \pm 0.23$ | $z=0.541$, $p=0.595$ | No effect |
| BR | $0.50 \pm 0.27$ | $0.62 \pm 0.36$ | $z=-1.494$, $p=0.151$ | No effect |
| TL | $0.59 \pm 0.31$ | $0.42 \pm 0.30$ | $z=1.889$, $p=0.073$ | No effect |
| BL | $0.63 \pm 0.36$ | $0.55 \pm 0.33$ | $z=1.209$, $p=0.209$ | No effect |
| total | $0.55 \pm 0.30$ | $0.51 \pm 0.31$ | $z=1.054$, $p=0.305$ | No effect |
| *C* | $0.41 \pm 0.08$ | $0.39 \pm 0.10$ | $z=0.713$, $p=.476$ | No effect |
| *Precision* | | | | |
| TR | $0.04 \pm 0.02$ | $0.06 \pm 0.02$ | $z=3.190$, $p<0.01$ | 0.49 |
| BR | $0.04 \pm 0.02$ | $0.07 \pm 0.02$ | $z=3.619$, $p<0.01$ | 0.59 |
| TL | $0.06 \pm 0.04$ | $0.07 \pm 0.03$ | $z=1.286$, $p=0.89$ | No effect |
| BL | $0.05 \pm 0.03$ | $0.07 \pm 0.03$ | $z=1.905$, $p=0.12$ | 0.29 |
| Total | $0.05 \pm 0.02$ | $0.07 \pm 0.02$ | $z=2.520$, $p=0.12$ | 0.39 |
| *C* | $0.03 \pm 0.01$ | $0.07 \pm 0.07$ | $z=-3.980$, $p<0.001$ | 0.61 |

Precision values reflect the RMS of inter-sample distances. *M* mean, *SD* standard deviation, *TR* top right, *BR* bottom right, *TL* top left, *BL* bottom left and *C* center, $r$ = Pearson's correlation coefficient indicates the effect size

VR and R with $F(3, 164)=2.531$, $p=0.059$. Based on the results of the ANOVA, relevant conditions were compared pair-wise by means of *t* tests, which revealed no significant differences between R and VR for each cross (see Table 1). The accuracy expressed by the degree of distribution in R and VR was around 0.5° (R = 0.55° and VR = 0.51°).

The precision values (see Table 1) were also analyzed for possible statistical differences between the crosses in task 1. The data across the different positioned stimuli were checked for normal distribution (Kolmogorov–Smirnov, $p<0.005$). A nonparametric Friedman test of differences was conducted and rendered a Chi-square value of 60.000, which was significant ($p<0.001$). There is a difference in gaze precision between VR and R regarding the different positions of the crosses (see Table 1). Bonferroni-corrected post hoc comparisons indicated a significant difference in gaze precision with partly strong effect sizes between VR and R, except for the top left cross.

In addition, the difference (in degree) of gaze accuracy between the center and the corners of the screen was examined. A nonparametric Friedman test of differences was conducted and rendered a Chi-square value of 18.43, which was significant ($p<0.001$). Bonferroni-corrected post hoc comparisons indicated that the mean score at the center of the screen in R ($M=0.41$, SD = 0.08) was significantly lower than at the corners ($M=0.55$, SD = 0.30). The same was observed in VR. The mean of the accuracy in the center ($M=0.39$, SD = 0.10) was also significantly lower compared to the mean of the corners ($M=0.51$, SD = 0.31). There was no significant difference between the center of R ($M=0.41$, SD = 0.08) and VR ($M=0.39$, SD = 0.10). No significant difference in gaze accuracy in the corners between R ($M=0.55$, SD = 0.30) and VR ($M=0.51$, SD = 0.31) could be observed. In contrast to accuracy, the precision values differ between R and VR for the stimuli placed in the center and corners (except top left).

#### 4.1.1 Discussion

The results show that there is no difference between R and VR within the directional vision measuring gaze accuracy. In VR, a better accuracy of 0.04° was obtained, which is not significantly different to R. Furthermore, for both conditions the highest accuracy was shown in the center of the field of view (FOV). The accuracy in the middle of the FOV, compared to the corners, was significantly better by 0.14° in R and by 0.12° in VR. The gaze accuracy (R = 0.55° and VR = 0.51°) is in line with the manufacturer's specifications, which stated a gaze accuracy of 0.5° (iViewETG User Guide Version 2.7 2016). The fact that the accuracy at the center of the FOV is more accurate than at the corners, is also in line with the study of Hornof and Halverson (2002). However, this was not observed in the study of Nyström et al. (2013), in which different calibration methods were tested. Targets placed off-center did not differ in offset as compared to those positioned centrally. This previous result shows that the lowest accuracy was detected in the lower right corner (Feit et al. 2017). The most inaccurate measurement in R was in the lower-left corner. The gaze data of the HMD in task 1 are in line with those from the mobile Eye-Tracking system. Regarding the current data, it can be concluded that the visual information processing related to stimuli in a short distance (a distance of 1 m), which are displayed in different directions, works similarly in VR compared to R. In the context of sports science, it is important to recognize a variety of visual stimuli and to react to them. The results of this task suggest that the operating mode of the visual system in VR can be carried out in the same way and the gaze behavior seems to be as accurate compared to R. Despite the significant differences within the precision values in the comparison between the realities, the quality of precision in VR is comparable with other devices and is precise enough to determine the parameters such as fixations and saccades.

## 4.2 Task 2: Pursuit eye-movements

To compare the data between VR and R of the infinity loop, the six fix points of the curve (Fig. 5) were selected.

The distance deviation was compared for each point in the infinity loop. A nonparametric Friedman test of differences among repeated measures was conducted and rendered a Chi-Square value of 118.38 which was significant ($p < 0.001$). Accordingly, the eye accuracy between the points differed. Bonferroni-corrected post hoc comparisons indicate a significant difference between each selected point (except for point 6) of the curve with strong effect sizes. The deviation of degrees shows a significantly lower accuracy for VR with 2.76° (SD 0.86°) compared to R with 0.72° (SD 0.12°) (Table 2).

### 4.2.1 Discussion

In the pursuit eye-movement task, a highly significant difference was found between VR and R in eye-tracking movements within gaze accuracy. Six points were selected from the infinity loop to make further comparisons between pursuit eye-movements in R and VR. The points were determined by six specific points in time, which were selected manually before. To successfully implement such a task in the Unity Engine, and to be able to extract valid data afterward, a different design than a PowerPoint presentation as a video on an object (monitor) in the virtual scene should be chosen. A possible approach would be to implement an object (in our case a point) into the VR scene and let it migrate as an infinity loop as shown in task 2. This would generate access to the $x$ and $y$ coordinates and could determine the exact time of the maxima of the curve. One possible explanation for these differences (except for point 6) seems to be the significantly poorer resolution of the HMD. It may have been more difficult in VR to detect the visual

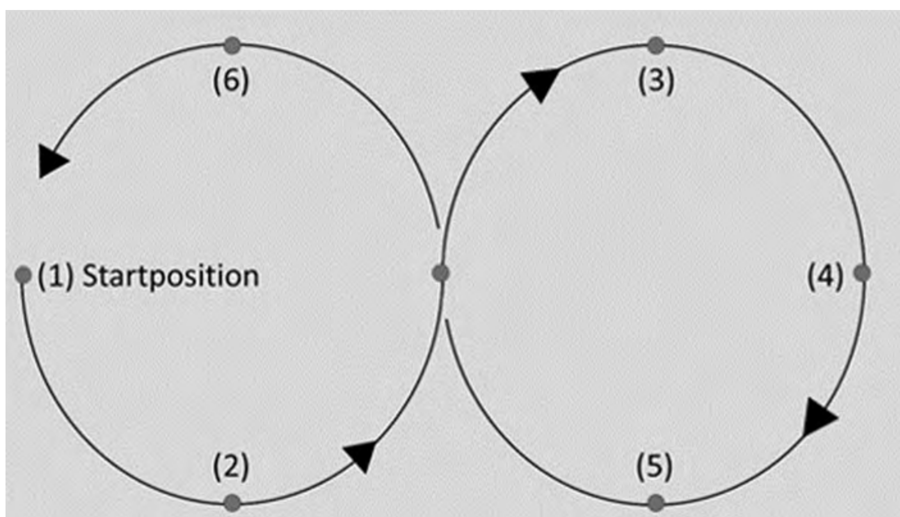


**Fig. 5** The six fix points of the infinity loop. The arrows indicate the direction of movement

**Table 2** Comparison between the gaze accuracy of R and VR by using the six points of the infinity loop as reference points (see Fig. 3)

| Position | R<br>$M \pm$ SD (deg) | VR<br>M $\pm$ SD (deg) | $z$ values, significance | Effect size ($r$) |
|---|---|---|---|---|
| 1 | 0.53 ± 0.32 | 3.34 ± 2.08 | $z = -6.725$, $p < 0.001$ | 1.04 |
| 2 | 0.68 ± 0.36 | 2.11 ± 0.68 | $z = -5.450$, $p < 0.001$ | 0.84 |
| 3 | 0.92 ± 0.55 | 4.05 ± 0.55 | $z = -4.500$, $p < 0.001$ | 0.69 |
| 4 | 0.52 ± 0.36 | 1.70 ± 0.57 | $z = -5.325$, $p < 0.001$ | 0.82 |
| 5 | 0.92 ± 0.46 | 2.59 ± 0.56 | $z = -4.275$, $p < 0.001$ | 0.66 |
| 6 | 0.73 ± 0.59 | 1.35 ± 0.86 | $z = 0.525$, $p = 0.645$ | No effect |

*M* mean, *SD* standard deviation, $r$ = Pearson's correlation coefficient indicates the effect size stimuli compared to R. This also emerged from the questionnaires of the participants, who experienced difficulties in perceiving the moving point in some places. In addition, the center of a circle may be more difficult to fixate than a center of a cross. This is, of course, a critical factor, especially concerning gaze accuracy. Authors emphasized the difficulty in distinguishing between system errors and a non-existent view of the target (Dalrymple et al. 2018). By using highly developed head-mounted displays, however, this factor could be limited. For faster movements, the authors suggested the use of devices with a higher measurement frequency, whereas 60 Hz is described as a too low frequency (Gibaldi et al. 2017). The frame rates of the different applications could differ (Clay et al. 2019). Although the current 3D scene was created without any complex computations, the quality of gaze measurements could have suffered, due to a limited synchronization and frame interpolation between the lower frame rate of the game engine (Unity) and the eye-tracker (Clay et al. 2019). Since gaze accuracy can also be influenced by calibration (Nyström et al. 2013), it should be mentioned that both devices (SMI mobile Eye Tracker and HMD integrated Eye-Tracker System) are based on a three-point calibration method that is system-controlled in VR and operator-controlled in R. Unfortunately, in our case, it was not possible to change the calibration method manually for the SMI devices. The operator-controlled calibration was shown to be preferred over the system-controlled calibration, which is considered the worst of all (Holmqvist et al. 2012). In general, they found that when participants were allowed to perform the calibration themselves, the accuracy and precision of the gaze data were significantly the best. Since no differences were found in the first task, the different calibration methods may affect the accuracy of a stimulus that moves continuously more severely than a static stimuli in VR. This could be verified by testing devices against each other by using the same calibration method while examining moving targets. Another reason could be the lack of experience of the participants within the VR. Only six of them had previous experiences but did not have their own VR glasses for private use, which suggests that their experience was relatively low. The results of the questionnaire show that one of them needed a break or complained about cybersickness. Nevertheless, to pursue a moving stimulus seems to be a challenge for the current used VR application. Therefore, a similarity of gaze accuracy between VR and R must be falsified. According to the results from the current study, the accuracy of the visual system in VR is much worse for dynamic stimuli and should be considered during the development of moving visual cues.

## 4.3 Task 3: Static gaze behavior at different distances

### 4.3.1 Between-condition comparison

A nonparametric Friedman test of differences was conducted and rendered a Chi-square value of 37.952, which was significant ($p < 0.001$). There is a difference in gaze accuracy over the different positioned stimuli (see Table 3). Bonferroni-corrected post hoc comparisons indicated that there is no significant difference between VR and R for the 1 m condition. The Wilcoxon test shows that there was a medium-strong significant difference between VR and R from the measurement of the deviating distance overall in gaze accuracy. The precision data revealed no normal distribution (Kolmogorov–Smirnov, $p < 0.001$). A nonparametric Friedman test of differences was conducted and rendered a Chi-square value of 67.449, which was significant ($p < 0.001$). In this task, there was also a difference in gaze precision between VR and R. Bonferroni-corrected post hoc comparisons indicated a difference for the 1 m condition ($z = 2.905$, $p < 0.001$, effect size $r = 0.45$), for the 2 m condition ($z = 2.333$, $p < 0.001$, effect size $r = 0.36$), and for the 3 m condition ($z = 2.810$, $p < 0.001$, effect size $r = 0.43$).

**Table 3** Comparison between the gaze accuracy and precision of R and VR of the different distances between the conditions (R vs. VR)

| Distance (m) | R<br>$M \pm$ SD (deg) | VR<br>$M \pm$ SD (deg) | $z$ values, significance | Effect size ($r$) |
|---|---|---|---|---|
| *Accuracy* | | | | |
| 1 | $0.41 \pm 0.08$ | $0.39 \pm 0.10$ | $z = 0.571$, $p = 0.322$ | No effect |
| 2 | $0.21 \pm 0.00$ | $0.38 \pm 0.12$ | $z = -1.190$, $p = 0.39$ | 0.18 |
| 3 | $0.17 \pm 0.04$ | $0.38 \pm 0.09$ | $z = -2.667$, $p < 0.001$ | 0.41 |
| Total | $0.27 \pm 0.15$ | $0.39 \pm 0.21$ | $z = -2.068$, $p = 0.039$ | 0.32 |
| *Precision* | | | | |
| 1 | $0.03 \pm 0.01$ | $0.07 \pm 0.07$ | $z = -2.905$, $p < 0.001$ | 0.45 |
| 2 | $0.03 \pm 0.01$ | $0.07 \pm 0.12$ | $z = -2.333$, $p < 0.001$ | 0.36 |
| 3 | $0.03 \pm 0.01$ | $0.08 \pm 0.09$ | $z = -2.810$, $p < 0.001$ | 0.43 |
| Total | $0.03 \pm 0.00$ | $0.07 \pm 0.09$ | $z = -4.015$, $p < 0.001$ | 0.62 |

*M* mean, *SD* standard deviation, $r$ = Pearson's correlation coefficient indicates the effect size

Regarding the comparisons between R and VR, there is no significant difference at the 1 m distance. A significant difference was observed for the 2 m distance, but only with a small effect size. The difference is more obvious within the 3 m distance where a large effect was detected. Compared to the results of task 1 (see Table 1), gaze accuracy seems to be at its best level in the center of the screen in both conditions (R and VR). The quality of gaze accuracy is influenced by the position of the presented stimuli, as it decreases when fixating at larger eccentricities. These results are an additional factor that proves the similarity of gaze accuracy in both systems (mobile Eye-Tracker in R and Eye-Tracker in HMD, both SMI). For precision, no significant differences could be found between the center and the corners of the screen ($p > 0.05$).

### 4.3.2 Within-condition comparison

The differences over the distances can be explained through the different characteristics of the continuity of each measurement system (see Table 4). In VR, the system works constantly regarding the gaze accuracy over the three fixation crosses at different distances. Therefore, no statistical difference between 1 m, 2 m, and 3 m in VR-condition was observed (all $p > 0.05$). It turned out that the course of the accuracy differed within both measuring systems. In VR, the accuracy remained at the same level over the three distances. When comparing the distances among themselves, no significant difference was detected (all $p > 0.05$). By focusing on the R-condition, we found differences between 1 and 2 m and between 1 and 3 m. No significant difference between the 2 m and 3 m distance was detected. The differences between R and VR can be explained by the continuous improvement in gaze accuracy over further distances with the mobile eye-tracker (R). For further detail, see Table 4.

Similar to the accuracy, the precision values in R decrease with increasing distance, while they remain relatively constant in VR. However, in contrast to accuracy, the changes within each condition are not significant ($p > 0.05$).

**Table 4** Comparison between the gaze accuracy and precision of R and VR of the different distances within each condition, $r$ = Pearson's correlation coefficient indicates the effect size

| Condition | Distance | $z$ values, significance | Effect size ($r$) |
|---|---|---|---|
| *Accuracy* | | | |
| *R* | | | |
| | 1 m versus 2 m | $z = 1.952$, $p = 0.001$ | 0.30 |
| | 2 m versus 3 m | $z = 0.952$, $p = 0.099$ | No effect |
| | 3 m versus 1 m | $z = 2.905$, $p < 0.001$ | 0.45 |
| VR | | | |
| | 1 m versus 2 m | $z = 0.190$, $p = 0.741$ | No effect |
| | 2 m versus 3 m | $z = 0.524$, $p = 0.364$ | No effect |
| | 3 m versus 1 m | $z = 0.333$, $p = 0.564$ | No effect |
| *Precision* | | | |
| *R* | | | |
| | 1 m versus 2 m | $z = 0.190$, $p = 0.741$ | No effect |
| | 2 m versus 3 m | $z = 0.429$, $p = 0.458$ | No effect |
| | 3 m versus 1 m | $z = 0.619$, $p = 0.284$ | No effect |
| VR | | | |
| | 1 m versus 2 m | $z = 0.667$, $p = 0.248$ | No effect |
| | 2 m versus 3 m | $z = 0.143$, $p = 0.805$ | No effect |
| | 3 m versus 1 m | $z = 0.524$, $p = 0.364$ | No effect |

**4.3.2.1 Discussion** In the third task, no differences in gaze accuracy were found between VR and R at the 1 m distance, similar to task 1. Within 2 m distance, there is a significantly lower accuracy in R compared to VR, but with a small effect size. Only from a distance of 3 m, a large effect was observed. These differences increase if the pixels are not adjusted over the distances in R. Accordingly, it must be taken into account that the number of pixels of a 2D image is distributed differently in size to different distanced objects in the scene. In VR, the coordinate system of the game engine (Unity3D) can be used and the relations between pixel and real distance are calculated automatically. While the accuracy of the R-condition improves with increasing distance, it remains constant in VR (see Table 3). The results are not surprising. The lower screen resolution in VR compared to R could lead to difficulties in perceiving the center of the fixation cross. In R, they still could perceive the center, whereas in VR, they often reported focusing just at the white fixation cross which reveals no accurate observation. Nevertheless, the deviation of the fixations produced by the participants from the target stimulus in VR is only around an angle deviation of 0.39°, which reveals a sufficient ability to observe other people or objects in daily situations or more specifically opponents, teammates movements', or sport equipment motions in sports scenarios. The different deviations of the two measuring systems might be affected by the different quality of stimuli presentation. The accuracy of the visual system can also be described as sufficient in this task. Compared to the fixation crosses performed in the current study, the stimuli from the sport science context (ball, bat, opponent, teammate, body regions, etc.) are much larger and therefore easier to recognize in VR.

The precision values differ between R and VR for all distances with strong effects (see Table 3). Nevertheless, the precision values of the integrated eye-tracker in the HMD are still comparable to those from other measurement systems mentioned by Nyström et al. (2013). This allows the detections of fixations and enables a comparison between individuals during participants' activities or sports performances in VR. Nevertheless, when observing the standard deviation (SD) of the precision values (see Table 3), abnormally high values could be detected. The HMD rendered two images for both eyes at the same time to create a stereo view in the VR. However, there seems to be a dark area in the middle of FOV, which blocked the real content in the scene when the user stared at this area. In this task, the cross was placed right in the middle of the screen for observation. When this cross was rendered for each eye, its position in the FOV was very close to this blocked area and this may explain the large SD value in precision because the participant was trying to find the cross in the middle (see Fig. 3). In the first task, however, these high values within the SD were not observed (see Table 1). This leads to the assumption that the discrepancy is not only due to the stimuli placed at different positions in task 3 but that it is also an issue due to different kinds of stimuli presented in each task (see Fig. 3).

## 5 General discussion

In the current study, the accuracy and precision of the visual system were measured and compared between the real and virtual conditions. Different stimuli were used to confront the visual system in various ways. The static crosses were placed at the corners of the screen and in the center. In addition, the participants had to permanently observe a point moving across the screen presented as an infinity loop. Furthermore, the participants had to look at static crosses in the center of the monitor. By modifying the monitor's position in relation to the participant, the fixations took place at different distances. The three tasks were chosen because an easily feasible implementation of the study in VR could take place. Due to the reference cross in the center of the screen, it was easy to calculate the length of the gaze vectors as well as the distance between the position of the target and participants' gaze point. These should be the first step to compare gaze accuracy and precision between R and VR. Perceiving stimuli placed on different positions at the monitor is an often-used method to calculate participants' gaze accuracy and precision (Feit et al. 2017; Hornof and Halverson 2002; Holmqvist et al. 2012). Since the manufacturer of the mobile eye-tracker and the integrated eye-tracker is the same in the HMD, a better insight into the behavior of participants was attempted to reach. The assumption that each device is equipped with the same technique and uses the same algorithms allows the conclusion of possible differences of the two systems due to foveal gaze behavior of the participants.

The within-subject design allows a direct comparison of VR and R. Each participant underwent the VR and R scene, which reduced the possibility of finding differences in the results due to different eye physiologies, varying neurology, and psychology, different ability to follow instructions, wearing glasses or contact lenses or having long eyelashes or droopy eyelids, which all can influence the quality of the data (Nyström et al. 2013). The homogeneity of the testing participants was ensured. Therefore, sports students at the same age and pedigree were chosen for participation in the current study. Participants wearing glasses were rejected due to problems with the installation of the different hardware systems simultaneously. However, no official test design for eye quality was conducted, which could be helpful to exclude possible outliers. Also, Nyström et al. (2013) stated the operator's experiences could affect the data quality. For each R and VR, only one operator was involved in the conduction to reduce possible influences. Both of them were well instructed and had to go through several test runs before starting the experiment.

Throughout the results of task 1, it can be said that the gaze accuracy within VR coincides with that of reality. Therefore, the greatest similarity occurred at a distance of 1 m. Although there is a difference between the two measurement systems at further distances, the calculated accuracy in the VR is still sufficient to ensure that the participants consider the implemented stimuli in the experiment. Since the lower resolution made the perception of the stimuli more difficult, it is conceivable that these differences would no longer occur with a higher resolution.

Looking at the 1 m distance, the accuracy does not differ between R and VR. Nevertheless, even if the values differ at different distances between the conditions, there is no concern with static stimuli. Previous studies have shown that values from 0.7° to 1.3° are found to be an acceptable indicator for SMI applications (Blignaut 2009). For dynamic stimuli presented in task 2, critical values that are above this defined threshold were found. When considering the precision of all tasks, the values are similar to those of the studies carried out so far, even if other systems were used (Holmqvist et al. 2011). To verify the accuracy and precision only from the influence of the measuring system, it is recommended to use an artificial eye, as it does not generate any movements of its own, where precision values of 0.001°–1.03° were observed (Holmqvist et al. 2011). To be able to make further conclusions here, more data needs to be generated with other HMDs since the data between tower-mounted and remote devices already differ. Furthermore, the limitation that the calibration method brings with it should be discussed. In VR, a system-controlled calibration method was used, which in any case is valid for the lowest precision value compared to the other methods (Nyström et al. 2013). An Implementation of a self-executable calibration method of the integrated eye-tracking system in HMD could increase the accuracy to set the fixated positions at the right time. If a technical implementation was provided, an examination with an artificial eye would be helpful to test the true values of both precision and accuracy (Nyström et al. 2013). Poor precision can be determined by the quality of the eye camera and the algorithms that determine the position of the pupil and the corneal reflection. The only constant that the VR environment creates is the lighting condition. To check this more in detail, other VR devices that have an integrated eye tracker should be tested. Higher developed devices with higher resolution should be integrated since lower resolution could lead to lower precision values. The eye-tracker in VR records data with a lower frequency than the mobile one that was used for R. However, recording samples with 30 Hz compared to those of 60 Hz have no impact on precision values (Ooms et al. 2015).

In the current study, the participants were placed in a seated position in front of a monitor and the visual stimuli were presented via an integrated PowerPoint presentation. This setup does not provide any information about gaze behavior to a highly dynamic situation in real-world sports. Kredel et al. (2017) suggest testing the sports-related perceptual-cognitive skills under more realistic conditions. Nowadays, mobile eye-trackers can be connected to smartphones or portable laptops, which ensures the recording of eye movements during the performance of more complex or extensive movements compared to those of the current study. The mobility of the integrated eye-tracking system in the HMD is restricted due to the length of the cable and is therefore difficult to use during real-world sports scenarios, as it occurs in most of the HMD eye trackers (Clay et al. 2019). An additional technical factor could be latencies that can occur due to the representation of the VR scenario of the game engine through the cable-based HMD. Further investigations have to be done to reveal those durations. Normally, the mobile eye-tracking system provides an external camera that shows the gaze pattern of the point of regards distributed over the FOV. Predefined Areas of interest (AOI) were used for analyzing the gaze pattern. This function can also be implemented in the VR since AOIs can be freely chosen via the integration of objects getting hit by a gaze vector. In addition, it is possible to trace the time when previously defined regions were looked at (Clay et al. 2019). Therefore, a comparison between both conditions can be ensured. Nevertheless, this study does not comply with all quality criteria for sports-related eye-tracking research because of the missing realistic viewing condition or naturalistic response like real movements (Kredel et al. 2017). Further studies need to be conducted, which have to meet these criteria and at the same time measure the gaze behavior of the participants conducting sports activities. Fast head movements could be the most challenging factor that needs to be solved.

In sports, it is also fundamental to perceive other objects in the environment without fixating them by using the peripheral vision (Vater et al. 2017). The current study is focusing on the foveal vision. Since peripheral vision plays an important role in the decision to act, this should also be investigated in a further study in VR. The results show that as long as the visual stimuli are well represented in the VR environment and a smooth perception can occur, studies can also be carried out with this application. The current results endorse the use of gaze data in VR. As long as the headset is mounted correctly on the head and the additional time for the re-calibration procedure can be accepted, Eye-Tracking in VR is considered to be a useful tool (Clay et al. 2019).

## 6 Conclusions

The results of the present study show that regarding the 1 m distance and static visual stimuli equal gaze accuracy between VR and reality could be observed. For precision, a worse result has been detected. Despite the difference to the mobile eye tracker, the integrated system in the HMD works precisely enough, as can be seen from the small deviations of the precision values. The results reflect realistic values so that an analysis of gaze behavior can also be carried out in the VR with reliable and valid data for fundamental research. We assume that an improved resolution of the HMD and the presentation of easily recognizable stimuli lead to accurate and precise fixations. When stimuli can be detected without any difficulties by the user, VR can be a valuable possibility to create sport relevant training scenarios with individualized visual cues. Based on the results of the current study, dynamic stimuli were perceived worse that static ones. Moreover, the stimuli moved in a predictable path, which does not correspond to realistic conditions. For this purpose, further data with improved measurement techniques and extended stimulus presentation (size, predictable and unpredictable trajectories, distance, characteristics, etc.) must be collected. During the conduction of the current study, the distances of the experimental setup always remained the same in VR, since they were fixed in the scene and therefore allow accurate measurements and controlled conditions. The current VR applications can already create a good feeling of immersion that encourages the user to act as in reality. However, to do more than just fundamental research, the technical components need to be improved. Further investigations in a more realistic scene have to be done to provide suggestions on how visual training in VR should look like for improving athletes' performances.

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**A.2** Spatial orientation in virtual environment compared to real-world

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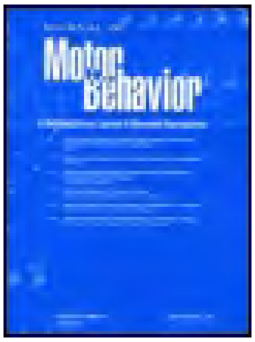

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ARTICLE

# Spatial orientation in virtual environment compared to real-world

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**ABSTRACT.** Virtual reality (VR) is popular across many disciplines and has been increasingly used in sports as a training tool lately. However, it is not clear whether the spatial orientation of humans works equally within VR and in the real-world. In this paper, two studies are presented, in which natural body movements were allowed and demanded. Firstly, a series of verbal and walking distance estimation tests were conducted in both the virtual and the real environment. The non-parametric Friedman test with pairwise comparisons showed no significant differences neither in verbal nor in walking distance estimations between the conditions (all $p > 0.05$). However, shorter distances (0.9-1.5 m) were estimated more precisely than larger distances (2.6-2.8 m) in both environments. Secondly, a self-developed route recall test to examine the spatial orientation was performed in the virtual and the real environment. The participants visually perceived the predefined route and were instructed to follow these routes with their eyes blindfolded and afterward to return to their starting position. Between the ending and the starting position, no difference between the two environments was observed ($p > 0.05$). Based on these two studies, the performance of the human spatial orientation preliminarily verified the same in a virtual and real environment.

*Keywords:* virtual reality, spatial orientation, visual perception, distance estimation, route recall

## Introduction

The rising popularity and huge amount of applications in virtual reality (VR) are booming in the last few years due to the fast development of technology. The customizable scenario, intuitive interaction, and high fidelity of the virtual environment grant the users to immerse themselves into a wide range of contents and applications, such as medical procedure training, rehabilitation, and sports performance enhancement (Akbaş et al., 2019; Michalski et al., 2019).

Some studies showed that VR can be a valuable tool across different fields. For example, children with a physical disability could benefit from VR and improve their spatial orientation by exploring the virtual environment regardless of the physical constraint in the real-world (Stanton et al., 1998). Both, VR and the traditional PC platform, can help the patients with major depressive episodes obtain a good transfer effect on a daily shopping task (Dehn et al., 2018). With the easily controlled scenarios in VR, other studies also suggested that VR training may serve as an alternative or useful addition during rehabilitation for patients with a cognitive disorder, such as traumatic brain injury or Alzheimer's disease (Riva et al., 1998; Rizzo et al., 1997). However, proper precautions should be considered to prevent or reduce the cybersickness (physical discomfort due to the stay in VR) before the VR application is implemented (Petri et al., 2020)

As the virtual environment can be easily tailored and modified pursuant to the demand, VR is suitable for the purpose of testing and analyzing spatial orientation by creating or manipulating the visual illusions (Buckely et al., 2016; Wilson & Soranzo, 2015). The human spatial orientation comprises of egocentric reference systems and environmental reference systems. These two systems work smoothly in various activities of our daily living, such as work or exercise and sports. The egocentric reference systems specify location and orientation relative to the observer while the environmental reference systems use the positional relations of surrounding objects (A. L. Shelton & McNamara, 2001). For example, to perform a successful return in a tennis game, the players need to accurately perceive the position of the fast-incoming ball while moving (egocentric reference systems) and hit the ball to the desired location on the other side of the court (environmental reference systems). All these interactions are considered based on visual perception, and the performance may differ in VR due to the perceived positional shift of the virtual objects (Kelly et al., 2017).

To determine the position of a virtual object in a virtual scene, the visual system relies on the distance and depth indicators such as convergence, the field of view (FOV), and occlusion (Ghinea et al., 2018). Some studies showed that the distances in the virtual world were often perceived shorter than they really were (i.e. underestimation of distances) (Knapp & Loomis, 2003; Messing & Durgin, 2005; Renner et al., 2013). This may result from the limited display performances such as vergence accommodation conflict, the image quality, the light, motion parallax, and dimension of the FOV (Ghinea et al., 2018) and through the nature of computer graphics (Kunz et al., 2009). This underestimation in VR was often observed from the egocentric perspective (Buck

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et al., 2018). Intrinsic individual components and environmental characteristics must be considered since they also influence spatial orientation (Cushman et al., 2008; Diersch & Wolbers, 2019; Notarnicola et al., 2014; Péruch et al., 1997; A. L. Shelton & McNamara, 2004; Tarampi et al., 2016; Wolbers & Hegarty, 2010). Therefore, interindividual and intraindividual differences in choosing the orientation strategies may vary and are highly relevant to the orientation performance (Diersch & Wolbers, 2019; Maselli, 2015). When designing experiments to examine the quality of distance estimation, it is necessary to not only include the measurement of verbal estimated distances. Most studies also included distance estimations by walking them. For example, it was shown that computer graphics influenced the verbal distance estimations, but did not show any significant impact on walking estimations (Kunz et al., 2009). Besides, previous studies mentioned that the motion of the human body is an important factor to measure distances. It is suggested that variables which encompass the limbs in coordination are responsible for human odometry (M. T. Turvey et al., 2009). Therefore, investigations of a homing task with blindfolded human participants were often used for examining the quality of distance estimations.

Spatial orientation is important in most of the daily movements and tasks as well as in sports scenarios. Many terms are used when it comes to spatial orientation, and many components are included. One of those is the spatial navigation, which is described as a cognitive function or as an ability to maintain a sense of direction and location while moving around (Wolbers & Hegarty, 2010). The visual-spatial skill is another key component to build up a cognitive map of the surroundings for an accurate spatial orientation (Wolbers & Hegarty, 2010). The visual-spatial skill consists of a set of sensory-motor control systems, including the sensory input from vision, the proprioception, and the vestibular system (Notarnicola et al., 2014). Among these sensory systems, the vision plays a predominant role in providing information about the spatial surroundings (Péruch et al., 1997). In addition, spatial memory is an indispensable factor to use visual cues for navigation and it is orientation-dependent to establish a spatial reference system when it comes from a single perspective (A. L. Shelton & McNamara, 2004). Cao et al. (2019) described an example of the efficiency of an evacuation from burning buildings. Wayfinding is defined as 'a cognitive process that involves the ability to learn a route and retrace it from memory to guide the move from one place to another, and judge the spatial information between people, objects, and surrounding environment' (Cao et al., 2019). The authors also emphasized the importance of the ability to build up cognitive maps in order to successfully complete wayfinding tasks, which is in line with previous findings (Cao et al., 2019; Kitchin, 1994; N.J. Mackintosh, 2002). Wolbers and Hegarty (2010) gave an overview of the different components that are included in spatial navigation. In the current study, the focus is the comparison between VR and real-world of egocentric distance perception and route recreation included homing in phase. Due to the lack of studies, it is still unclear whether the distance perception and estimation would show the same performances in VR and in real-world. Distance perception is just one of many factors that help us to orientate in an unknown environment. Distance estimates have already been studied in VR using the HTC Vive (Kelly et al., 2017). With further examinations, we concentrated on the comparison between distance perceptions in real and virtual environments. Besides, we wanted to analyze the active movement in a virtual environment, where distances could be estimated with similar qualities regarding both conditions. Here, we saw a deficit in most studies, since the actual wayfinding capabilities were often neglected (Cao et al., 2019). In addition, in most of the studies, the participants were limited to only move their position inside the virtual scene using a joystick instead of moving their location intuitively by walking freely (Dehn et al., 2018). In general, the comparison of the visual perception between a virtual scene and in a real environment has rarely been made and differences between them may occur through technical limitations (Pastel et al., 2020). It is extremely important to clarify any relevant differences between VR and reality before more VR applications or therapies using VR to be further implemented. Therefore, the aim of the current paper was to analyze the differences between VR and reality in distance perception (study 1) and in spatial navigation (study 2) separately. To eliminate the influence of possible differences in distance estimations, the route properties (length and width) consisted from previous examined equal distance estimations in both conditions. The results of previously mentioned studies on distance estimation have shown that distances can already be estimated well with older VR models. Due to high-developed computing systems, detailed and realistic looking scenes can be created and the same information can be gained using perceptual skills. Therefore, no differences can be assumed as long as the task demands do not exceed the technical and practical issues.

## Methods and Results

Two within-subject-studies were designed and conducted in accordance with the declaration of Helsinki. The approval of the local ethics committee of the authors' university was obtained.

## Experimental apparatus for both studies

### Hardware

In both studies, an HTC Vive (HTC, Taiwan) was chosen with a field of view of 110 degrees. To execute the VR environment smoothly, a high-performance desktop equipped with Intel i7 CPU, 16 GB memory, 512 GB SSD, and Nvidia GTX 1080 8GB graphics card was used. A motion capture system (Vicon, Oxford, UK) including 13 cameras with a sampling rate of 200 Hz was used for study 2.

### Software

In order to create an environment of high fidelity preventing the participants from a conflict between the real-word and the virtual environment, two virtual rooms were created with Blender using the scales and the textures of the objects in the real-world. These rooms were also used during the experiments in the reality in these studies. The created virtual environments were then imported into Unity3D (version 2019.1), and the SteamVR (version 2.5.0) was used to enable users to interact in the virtual reality. Visual Studio 2017 was used for implementing the C# program for Unity to control the studies.

The results of the studies in the next section were processed and calculated with MATLAB 2018b. Finally, statistical analyses were performed with SPSS ($\alpha = 0.05$) and the relevant and detailed statistical methods are explained later. An additional factor of over- and underestimations were also considered.

## Study 1: Distance perception

The aim of the study was to highlight the difference between real-world and VR in distance estimation. Furthermore, the verbal estimations were compared with the walking estimations. It was also examined whether there was a difference between the nearer and farer distances later distinguished in the next chapter. All comparisons were made within and between each condition.

### Participants and experimental setup

Twenty-one young sport students (11 males and 10 females, age $22.79 \pm 3.12$) participated in this experiment on a voluntary basis with normal or corrected to normal vision, no report of eye or neurological impairment. The participants gave their written consent after fully understanding the aim and the procedure of the study. Eight participants had already gained VR experience, but none of them possessed an own VR application. VR experience was noted down when the participants had either taken part in at least one VR study or had ever participated in a VR gaming session. 11 participants regularly played video games ($M = 4.58$ hours per week, $SD = 2.51$). To test the distance perception, five different distances were marked shown with a yellow stick in real-world and in VR on the ground, which were 0.9 m, 1.2 m, 1.5 m, 2.6 m and 2.8 m away from the starting point (Figure 1). The chosen distances are common in many sports e.g. in karate regarding the variable interpersonal distances (Zhang et al., 2018) between two opponents or volleyball, where the athletes have to keep certain distances to the net. In addition, the distances were chosen due to the limiting length of the cable (5 m), which was connected to the HMD. We assured that no haptic feedback was provided, especially for the more distant target positions by making sure that the participants did not feel any pressure of the cable pulling on the HMD during their performances.

The aim was to investigate and compare those distances representing the personal space ($0 - 1.5$ m) and the action space ($1.5 - 30$ m) (Cutting & Vishton, 1995). During conduction, only one of the marked distances was shown at a time in randomized order to avoid any confusion to the participants. A guiding rope was placed alongside for the participants as a reference to walk forwards as requested during different experimental phases described in the next section. Each participant was tested in VR and reality, but the order of the conditions was randomized. The participants did not get any feedback of their accomplishments.

### Procedure

The experimenter explained the whole experimental procedure and measured the subjects' interpupillary distance to have a clear visual input from the HMD.

Afterwards, the participants were guided to the starting point. As shown in Figure 1, this was the perspective of a participant when s/he was standing at the starting point in both real-world (RW) and VR scenarios. In the VR part of the study, the HMD was calibrated by the experimenter using the official built-in calibration protocol from SteamVR. The participants could look and walk around in the VR scene during this 3-minute adjustment phase without seeing any distance cues. At this phase, the measurement tape and all the yellow sticks indicating the predefined distances were hidden and invisible to the participants. After the adjustment phase, the formal experiment started. Each of the five distances appeared twice in randomized order, so in total, ten trials were tested for each participant. For example, a yellow stick at one distance was displayed and the participant observed it from the starting position without moving. Then s/he was asked to estimate the distance and report it verbally in meters. The participants were not informed about how many different distances they should estimate, nor were they given any indication about the spatial size of the scene at the beginning of the experiment. After the verbal estimation, s/he put on the blindfold to block the vision and used the guiding rope to walk forwards to


**FIGURE 1.** Experimental setup for distance perception. Left: virtual reality (VR), right: real-world (RW). These are the perspectives of the participants standing at the starting point. Five distances were marked with yellow sticks but only one of them was shown in each trial during the data acquisition (here 0,9 m).

the distance s/he perceived before. In the RW part, the procedure was the same as in VR but without using the HMD, but their eyes were covered by a blindfold. The detailed procedure is shown in Figure 2.

### Data analysis and statistics

First of all, we analyzed possible differences between participants with previous experiences in VR compared to those without (see participant description). Therefore, we had two independent samples that differed in size. Eight of the participants had already experienced VR due to previous participation in other studies. The Shapiro-Wilk-Test revealed non-parametrically distributed data ($p<.05$). This test is known for its high statistical power (Ramsey & Schafer, 2013). Therefore, possible differences between the groups were analyzed using the Kruskal-Wallis-Test for each distance [0.9 m, 1.2 m, 1.5 m, 2.6 m, 2.8 m] in each condition [verbal, walking]. No significant difference between the groups for each distance was detected ($p>.05$). Therefore, for further statistical analyses, the whole data set was treated as a homogeneous group.

The Shapiro-Wilk-Test was used to examine the distribution of the data set. Due to the non-parametric distribution of the data ($p<.05$), the Friedman test was used to analyze the averaged deviations (m) from each target line in two conditions [verbal, walking] and over the five different distances [0.9 m, 1.2 m, 1.5 m, 2.6 m, 2.8 m] with post-hoc-comparisons using the Bonferroni correction and calculated Coheńs d effect sizes for the quality of accuracy. In addition, the Chi-square Test was used to compare the amount of over- or underestimations between VR and RW. The results are divided into two groups. We are interested in the absolute values and the percentage of the deviations for each distance occurring at the verbal and walking distance estimation. The percentage deviation is defined by the quotient of the difference between estimated and given distance and the given distance. The interim result was multiplied with 100.

### Results

*Within each condition (RW and VR) for verbal and walking distance estimations. Verbal distance estimation.* First of all, we examined how precisely the distances

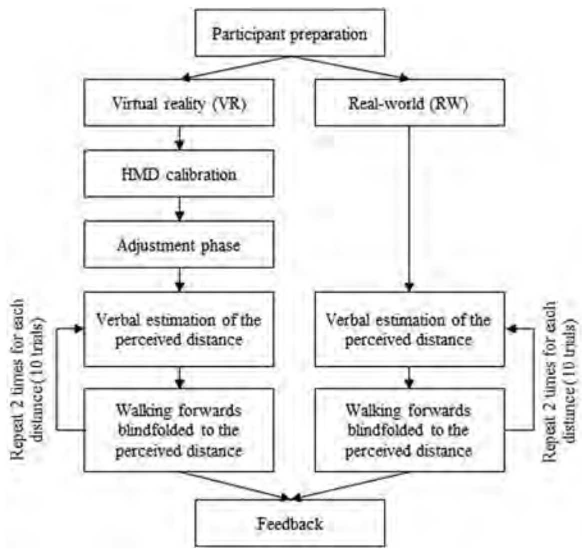


**FIGURE 2.** The procedure of study 1.

were estimated by the participants in each condition. For the verbal estimations, the non-parametric Friedman test of differences was conducted and rendered a Chi-Square value of 69.57, which was significant ($p < .001$). Regarding the first three distances, there was no difference in the estimations of distances given by the participants within each condition. The verbal estimations were significantly worse for the distances of 2.60m and 2.80m in comparison to the nearer ones in both RW and VR (see Table 1).

Since a difference between the distances was indicated by the Friedman test, we assumed that a higher inaccuracy of the verbal distance estimation is shown over the distance, so a possible deterioration with increasing distance was anticipated. In the real-world, the estimations up to the distance of 1.5 m did not differ significantly from the closer lines (see Table 1). For the 2.6 m distance, a significant difference with a medium-strong effect was detected and a strong effect for the 2.8 m distance compared to the deviation of the nearest line (0.9 m). In virtual reality, exactly the same occurred. Only for the distance of 2.6 m a significant difference with a strong effect was detected and a strong effect for the 2.8 m distance. In summary, the five different distances were equally difficult to estimate in virtual reality and the real-world. In VR, however, a strong effect was already seen at the distance of 2.6 m (see Table 1). Nevertheless, from this distance on there is a medium-strong effect in real-world as well. These results underline that verbal distance estimations from the VR are comparable to those from the real-world and lead the participants to get a good impression of the scene.

The Friedman-test revealed significant differences in RW for the percentages of the verbal distance estimations ($\chi^2$ (4) = 33.657, $p < 0.001$). In VR, no significant differences were found (see Table 1).

*Walking distance estimations.* A non-parametric Friedman-test was conducted and rendered a Chi-Square value of 53.92, which was significant ($p < .001$). The estimations up to the distance of 1.5 m did not differ significantly from the closer lines (0.9 m and 1.2 m). Only from the distance of 2.6 m a significant difference with a strong effect was detected and a strong effect for the 2.8 m distance compared to the distribution of the nearest line (0.9 m). In VR, exactly the same was observable. Only for the 2.6 m distance a significant difference with a strong effect was detected and a strong effect for the distance of 2.8 m compared to the distribution of the nearest line (0.9 m). Thus, the non-verbal distance estimation also shows that the participants were able to assess the distances similarly well in both conditions (VR and R). From a distance of 2.6 m onwards, the participants seem to have more difficulties in estimating the walking distances. These results correspond to the verbal ones. However, the gap between the distance of 1.5 m and the 2.6 m distance does not appear as large as in the verbal distance estimations for both RW and VR (see Table 1). This is not in line with previous studies, that report that verbal distance estimation is mostly worse compared to walking estimations (Knapp & Loomis, 2003; Renner et al., 2013). Regarding VR, the participants seem to have more difficulties in verbal distance estimations compared to walking. These conclusions can be drawn from the percentages of the deviations from the different distances (see Table 1).

Regarding the percentages of walking distance deviations, no significant differences were found neither for RW nor for VR (see Table 1).

*Under- and overestimations of the distances.* Moreover, the number of participants who tend to under- or overestimated the distances were recorded. The Chi-square test revealed no difference between the VR and RW in the number of over- and underestimations within the verbal distance estimation ($\chi^2$ (1) = 2.54, $p = .11$).

In addition, no difference between the VR and R in the number of over- and underestimations within the walking distance estimation could be found ($\chi^2$ (1) = .009, $p = .925$).

*Between the conditions (RW vs. VR).* No differences were detetcted regarding the direct comparison between RW and VR for each distance in the verbal estimations: 0.9 m (p = .779), 1.2 m (p = .838), 1. 5 m (p = .252), 2. 6 m (p = .093) and 2.8 m (p = .959). In the walking distance estimations, also, no significant differences were

**TABLE 1. Comparisons within each condition of the verbal and walking distances estimations for each distance in real-world (RW) and virtual reality (VR). The absolute values and percentages are listed separately for each distance. In addition, no differences between the nearer distances (0.9 m, 1.2 m, 1.5 m) were detected. The absolute values were considered for the statistical analysis, because we examined the distance estimations deteriorated equally in both conditions.**

| Parameter/Distances | | 0.9 | 1.2 | 1.5 | 2.6 | 2.8 | Friedman-Test | Post-hoc tests | Cohen's d Effect-size |
|---|---|---|---|---|---|---|---|---|---|
| Verbal | | | | | | | | | |
| RW (absolute deviations) | $M \pm SD$ (in m) | 0.16 ± 0.09 | 0.18 ± 0.14 | 0.17 ± 0.14 | 0.31 ± 0.22 | 0.43 ± 0.23 | $p < .001$ | 0.9 – 2.6 $p < .05$ | 0.47 |
| | | | | | | | | 0.9 – 2.8 $p < .001$ | 0.92 |
| | | | | | | | | 1.2 – 2.6 $p < .05$ | 0.43 |
| | | | | | | | | 1.2 – 2.8 $p < .001$ | 0.88 |
| | | | | | | | | 1.5 – 2.6 $p < .05$ | 0.45 |
| | | | | | | | | 1.5 – 2.8 $p < .001$ | 0.90 |
| RW (percentages of deviations) | $M \pm SD$ (in %) | 17.51 ± 9.88 | 14.80 ± 11.58 | 11.38 ± 9.25 | 11.95 ± 8.43 | 15.48 ± 8.04 | $p < .05$ | 0.9 – 1.5 $p < .05$ | 0.58 |
| | | | | | | | | 0.9 – 2.6 $p < .05$ | 0.49 |
| | | | | | | | | 1.5 – 2.8 $p < .05$ | 0.45 |
| VR (absolute deviations) | $M \pm SD$ (in m) | 0.18 ± 0.09 | 0.17 ± 0.12 | 0.21 ± 0.15 | 0.52 ± 0.35 | 0.55 ± 0.33 | $p < .001$ | 0.9 – 2.6 $p < .001$ | 0.75 |
| | | | | | | | | 0.9 – 2.8 $p < .001$ | 0.85 |
| | | | | | | | | 1.2 – 2.6 $p < .001$ | 0.81 |
| | | | | | | | | 1.2 – 2.8 $p < .001$ | 0.91 |
| | | | | | | | | 1.5 – 2.6 $p < .05$ | 0.56 |
| | | | | | | | | 1.5 – 2.8 $p < .001$ | 0.65 |
| VR (percentages of deviations) | $M \pm SD$ (in %) | 19.52 ± 10.26 | 13.87 ± 9.65 | 14.05 ± 9.73 | 19.82 ± 13.65 | 19.55 ± 11.74 | $p > .05$ | – | – |
| Walking | | | | | | | | | |
| RW (absolute deviations) | $M \pm SD$ (in m) | 0.12 ± 0.07 | 0.19 ± 0.19 | 0.19 ± 0.12 | 0.26 ± 0.22 | 0.33 ± 0.19 | $p < .001$ | 0.9 – 2.6 $p < .05$ | 0.55 |
| | | | | | | | | 0.9 – 2.8 $p < .001$ | 0.90 |
| | | | | | | | | 1.2 – 2.6 $p > .05$ | – |
| | | | | | | | | 1.2 – 2.8 $p < .05$ | 0.69 |
| | | | | | | | | 1.5 – 2.6 $p > .05$ | – |
| | | | | | | | | 1.5 – 2.8 $p < .05$ | 0.59 |
| RW (percentages of deviations) | $M \pm SD$ (in %) | 13.28 ± 7.28 | 15.81 ± 16.13 | 12.35 ± 8.02 | 9.90 ± 8.60 | 11.71 ± 6.85 | $p > .05$ | – | – |
| VR (absolute deviations) | $M \pm SD$ (in m) | 0.15 ± 0.10 | 0.22 ± 0.13 | 0.20 ± 0.14 | 0.34 ± 0.18 | 0.38 ± 0.24 | $p < .001$ | 0.9 – 2.6 $p < .001$ | 0.73 |
| | | | | | | | | 0.9 – 2.8 $p < .001$ | 0.90 |
| | | | | | | | | 1.2 – 2.6 $p > .05$ | – |
| | | | | | | | | 1.2 – 2.8 $p < .05$ | 0.47 |
| | | | | | | | | 1.5 – 2.6 $p < .05$ | 0.59 |
| | | | | | | | | 1.5 – 2.8 $p < .001$ | 0.72 |
| VR (percentages of deviations) | $M \pm SD$ (in %) | 16.59 ± 11.24 | 18.08 ± 10.45 | 13.17 ± 9.33 | 13.13 ± 6.98 | 13.67 ± 8.68 | $p > .05$ | – | – |

found between RW and VR: 0.9 m ($p = .400$), 1. 2 m ($p = .088$), 1. 5 m ($p = .980$), 2. 6 m ($p = .083$) and 2.8 m ($p = .524$).

*Direct comparison between the walking and verbal distance deviations for each distance within each condition (RW and VR).* There are no significant differences between verbal and walking distance estimations in RW regarding the direct comparison between 0.9 m ($p = .201$), 1.2 m ($p = .917$), 1.5 m ($p = .876$), 2.6 m ($p = .262$) and 2.8 m ($p = .72$). In VR, the same results were found for each distance comparison, 0.9 m ($p = .361$), 1.2 m ($p = .303$), 1.5 m ($p = .676$), 2.6 m ($p = .273$) and 2.8 m ($p = .426$).

## Discussion

To verify the quality of distance estimations, we chose to conduct verbal and walking estimations like previous studies did (Knapp & Loomis, 2003; Messing & Durgin, 2005).

The participants estimated the distances verbally in the first method. In the second one, the participants' gait was measured. It is an action-based method for which the participants had to go blindfolded pathways (Willemsen & Gooch, 2002). Multiple dependent measures can be used to make more reliable statements about distance estimation or perception in the virtual world (Kelly et al., 2017). Based on previous research, in which the visual-spatial capacity between volleyball and tennis athletes and non-athletes were compared, we used a self-created test that allows us to determine the orientation ability of each participant in both conditions (RW and VR) (Notarnicola et al., 2014).

Kelly et al. assessed the perceived space in different tasks in a virtual environment by comparing modern and older HMDs. The participants completed a series of tasks, such as blind-walking and verbal distance estimation (Kelly et al., 2017). The results showed that in blind-walking tasks, the HTC Vive facilitated more accurate estimation of different distances in comparison to older displays and that they did not differ substantially from the real-world. The verbal estimation of distances in VR was not significantly worse than in the real scene either, which is not in line with previous studies (Kelly et al., 2017). The underestimation of distances was possibly reduced with a higher resolution display of the HMD (Kelly et al., 2017). Renner et al. proposed four potential factors for egocentric distance compression, which were measurement methods, technical factors, compositional factors, and human factors. After a walking interaction, the authors proposed a positive effect on blind walking judgments, whereas no effect could be observed in verbal distance estimations. Those differences could be explained through the different perceptual representations which differ based on the perceptual cues building up those representations (Kelly et al., 2017). In the current study, those differences were not verified and underestimations in VR were observed neither for the verbal estimations nor to the walking ones (see Figure 3).

Based on the theory that human odometry relies on gait-symmetry specific information, it can be explained that no differences between the conditions for walking distance estimation occurred (M. T. Turvey et al., 2009; M. T. Turvey et al., 2012). In general, no differences were found between the distance estimates in RW and VR. For larger distances, the estimations became worse in a similar proportion, which is in line with previous work (Kelly et al., 2004). However, it should be kept in mind, that changing the graphic quality has an impact on verbal distance estimations, but not on walking ones (Kunz et al., 2009). The authors stated that those differences are caused by different visual pathways for perceptual awareness and action that leads to different behavioral outcomes. Previous results also showed that body-based information is necessary to achieve a positive effect of distance estimations through interaction (Waller & Richardson, 2008). We ensured that the participants did not walk the distances heel-to-toe, because this would have led to difference with those participants, who had not chosen this strategy.

In summary, the comparison of the distance estimations in virtual reality and real-world revealed no significant difference neither for the verbal nor for the walking distance estimations. In both conditions, the deviations from the correct distances became become much worse from the 1.5 m distance onwards. It is not surprising that distances further away were estimated much worse than the nearer ones. The goal of the study was to see whether the loss of quality within the estimations occurred similarly in both conditions (RW and VR). An additional factor that should be eliminated is the different observing time of the participants. Each participant should state the estimated distance verbally. Afterwards, they could start if they felt ready. This observation time could have affected the quality of estimations and should be standardized in future research.

*Study 2: Spatial orientation/route recall.* The aim of the study was to find out whether the participants were able to follow a route marked on the ground by purely visual observation. For this purpose, we divided the route into a total of 6 sections. After the information of the surrounding environment was perceived, the view of the participants was blocked. Hereby, we wanted to check whether the visual information could be used equally in both conditions and could be evoked from memory. Respectively, we have defined the quality of the orientation based on the deviation from the previously defined turning points and considered the observation and execution time as a possible influence.

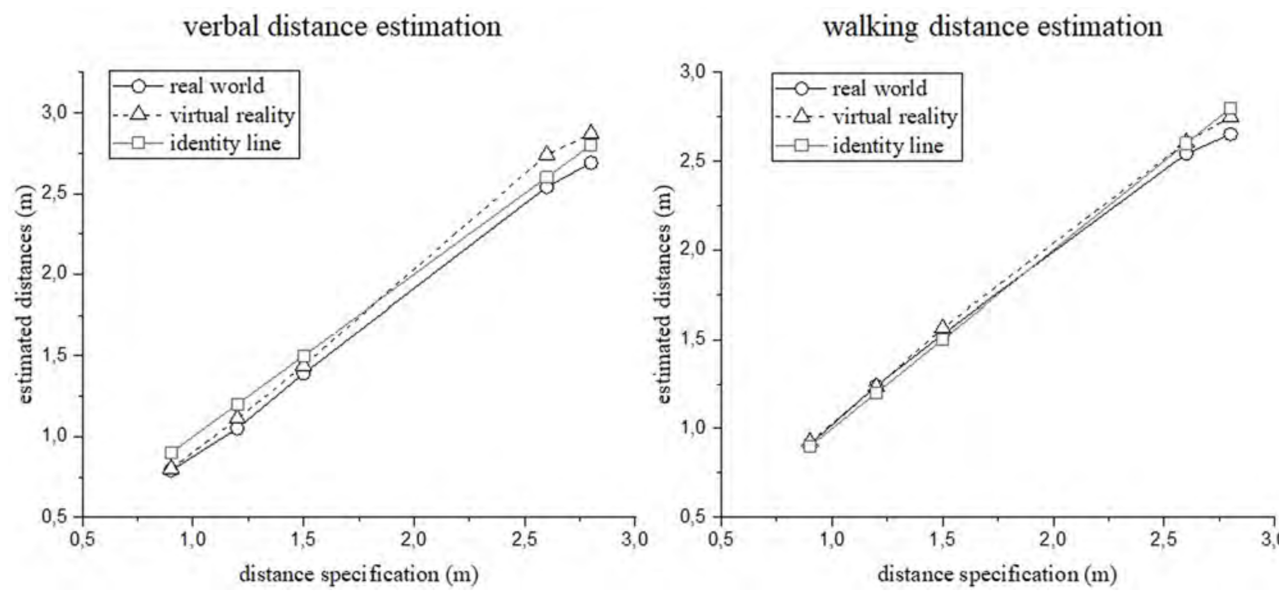


**FIGURE 3.** The absolute values are presented for each distance in both conditions for verbal (left side) and walking (right side) distance estimations. The identity line indicates perfect estimations.

### Participants and experimental setup

Fifteen young adults (8 males and 7 females, averaged age = 25.3 ± 2 years) were recruited in this study. The study was done in a gym equipped with a Vicon system as described previously. In the middle of the gym, a route was marked with white tape on the floor. The long segment of the route was 2.5 m, the short segment was 1m and the width of the tape was 5cm as shown in Figure 5. The route properties were based on technical factors and on the results of study 1, where no significant differences were detected between RW and VR in verbal and walking distance estimation. The route in VR was mirrored from RW to avoid learning effects from the same route during the procedure because of the new properties of the environment regarding the visual cues in the background. Six optical markers were placed on each turning point and the starting- and endpoint of the route. Three reflective markers, one on the chest and two at the center of each scapular, were placed on the participants to capture movement coordinates using the Vicon system.

### Procedure

Before the experiments started, the participants agreed and signed the consent form and then filled in a questionnaire regarding their previous experience in the VR, including VR gaming, immersive 360-degree movies, or other relevant applications. 8 participants stated having previous experiences of immersion in virtual environments. Next, the experimenter explained the whole experimental procedure and measured the participants' interpupillary distance to have a clear visual input from the HMD. Each participant completed the experiment in both conditions, but the order was randomized. Afterward, the participants were guided to the starting point as shown in Figure 5. To test the reliability of the self- created orientation test, which was based on Notarnicola et al. (2014), we decided to run a retest, which was taking place one week after the first testing.

The participants stood at the starting point and observed the route for 30 seconds (Figure 5). Similar to study 1, the observation was made from one perspective. After the observation phase ended, they put on the eye mask to block the sight in RW. In VR, the display of the HMD was turned off so the participants wouldn't see the environment. Then they started walking along the route until the endpoint, and returned to the starting point in the shortest way. The distance between the starting point and the position where the participant ended up was measured using the motion tracking system. The participants walked the route three times in each condition (i.e. RW and VR). The sequence of conditions was randomized and the routes were mirrored to avoid a possible learning effect.

### Data analysis

Similar to study 1, we tested possible differences between the participants having pre-experiences in VR and those without. Therefore, we split the data set into 4 groups [RW-pre-experiences, RW-none-pre-experiences, VR-pre-experiences, VR-none-pre-experiences] and compared the deviations for all route positions [1, 2, 3, 4, 5, 6]. The Shapiro-Wilk-Test revealed non-parametrically

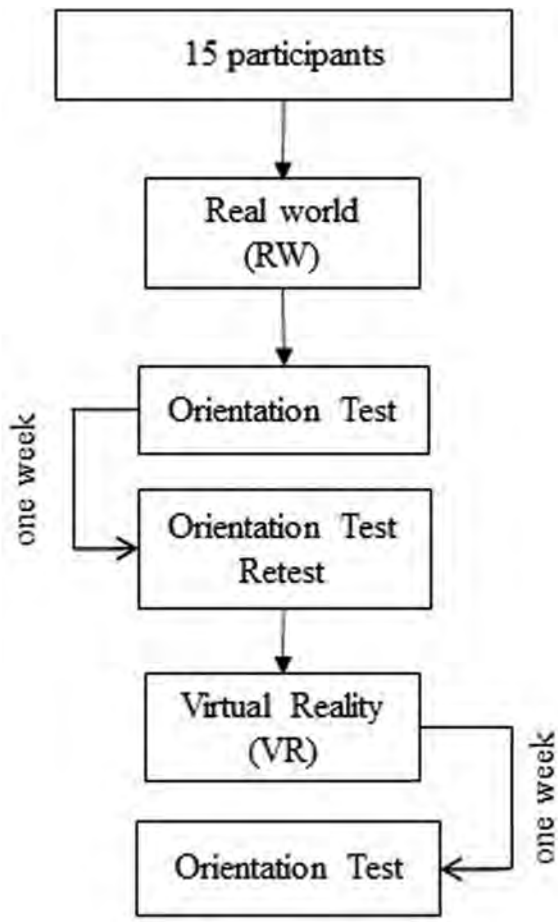


**FIGURE 4.** Experimental procedute for study 2.

distributed data (p<.05). The Kruskal-Wallis-Test showed no differences between the groups for each route position (p>.05). Therefore, we treated the data set as homogenous group and continued with further analyses. Due to the self-created test design, we decided to evaluate the reliability using the Bland-Altman plot analysis and in addition, we conducted a Friedmans two-way ANOVA with multiple rang tests and pairwise comparisons. The captured coordinates of both the route and the movement of the participants were processed and calculated in MATLAB 2018b. The non-parametric Friedman test with posthoc comparisons was conducted to compare the six points on the route between RW and VR (see Figure 4). We captured the position of each participant with three passive markers. The pathway of the route was also measured via markers using the Vicon system. Related to each marker position, the time point of rotation, and the distance deviation between the participant and the turning point were detected. The best trial of the participant was chosen for further data analysis. The results for the RW condition were derived from the first test. We compared each position pairwise in RW from the test and retest using the Wilcoxon signed-rank test (see Table 2). The defined pathway of the route and the individual ones from the participants were displayed via the Matlab script. Manually, the turning point was selected and the distance was calculated (two dimensional).

In addition, the observation times and execution times of the participants were recorded. The observation time is defined as the time during which the participants were allowed to see the route from the starting point for a maximum of 30 seconds. They were not obliged to use the whole observation time, but were free to start walking the route when they felt well prepared. The execution time was defined as the duration that the participants needed to get from the starting to the end position (see Figure 5). To compare the execution and observation times between the real-world and virtual reality, we conducted a Wilcoxon signed-rank test. For examining a possible influence of execution times and observation times on participants' performances, we calculated possible correlations between the defined times and the deviations around the last position (position 6, Figure 5). Due to the limited participants ($n = 15$), we used the spearman's rank correlation coefficient. According to Cohen (Cohen, 2013), values for d starting at 0.2 are representing a small effect, values for d $<=$ 0.5 a medium effect, and a d greater than 0.8 is defined as a strong effect.

## Results

To make further statistical analyses, the consistency of the self-created orientation test was examined. Therefore, the limits of agreement (LOA) described by Bland and Altman (Bland & Altman, 1986) were used to calculate the test-retest-reliability, as recently seen in biomedical literature (Weir, 2005). There was no difference between the RW test and its retest and no proportional bias could be observed. In addition, we found no significant differences for each route position between participants with or without previous VR-experiences. The non-parametric Friedman-test was conducted and rendered a Chi-Square value of 42.21, which was significant ($p < .001$). The differences between the deviations of the Orientation Test and Orientation Test-Retest were significant between Position 3 (Orientation Test) and Position 6 (Orientation Test-Retest) ($z = -5.467$, $p < .001$, Cohens effect size $d = 1.41$) and between Position 1 (Orientation Test) and Position 6 (Orientation Test-Retest) ($z = -4.667$, $p < .001$, Cohens effect size $d = 1.21$). However, if considering the direct comparison of each individual position (6 positions) of the Orientation Test and Orientation Test Retest, no differences can be found,

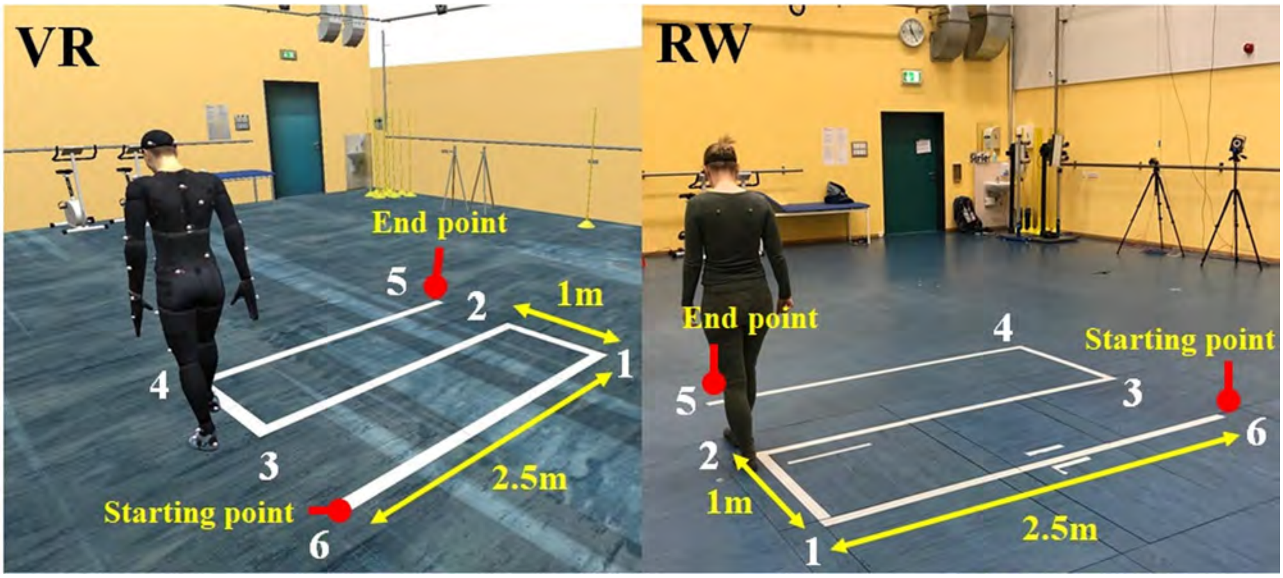


**FIGURE 5.** Experimental setup in VR (left) and RW (right) for Experiment 2. The route marked with tap on the ground was flipped intentionally to avoid learning effect from VR to RW or vice versa. The avatar in the left image is only for demonstration and was not displayed during the experiment. The numbers indicate the chronological turning points of the route. Point 6 is the last measured position, from which the participant returned to the starting point.

**TABLE 2. Comparison of the deviations for each turning point of the route between RW and VR.**

| Position | R<br>M ± SD (m) | VR<br>M ± SD (m) | z-values, significance | Cohen's d effect size |
|---|---|---|---|---|
| 1 | 0.13 ± 0.12 | 0.15 ± 0.12 | z = 0.133, p = 0.919 | no effect |
| 2 | 0.21 ± 0.17 | 0.17 ± 0.15 | z = −1.533, p = 0.244 | no effect |
| 3 | 0.10 ± 0.12 | 0.35 ± 0.34 | z = −3.733, p = .005 | d = 0.96 |
| 4 | 0.16 ± 0.12 | 0.39 ± 0.38 | z = −3.133, p = .017 | d = 0.81 |
| 5 | 0.48 ± 0.40 | 0.31 ± 0.29 | z = −1.867, p = 0.156 | no effect |
| 6 | 0.37 ± 0.24 | 0.37 ± 0.30 | z = −0.400, p = 0.761 | no effect |

position 1 (p = .960), position 2 (p = .800), position 3 (p = .288), position 4 (p = .206), position 5 (p = .156) and the position 6 (p = .478). For this reason, the orientation test was also conducted in VR.

The test results of the first measurement in RW were compared to the ones in VR. A non-parametric Friedman test of differences was conducted and rendered a Chi-square of 33.779, which was significant ($p < .001$). A difference in walk accuracy over the six different positions was observed. Post-hoc comparisons using the Bonferroni test indicated that there was no significant difference between VR and RW at position 1, 2, 5, and 6 (see Table 2). The deviation of walking differed between VR and RW for position 3 (z = −3.733, $p < .05$, Cohen's effect size $d = 0.96$) and 4 (z = −3.133, $p$ = < .05, Cohen's effect size $d = 0.81$).

*Times.* Due to the reduced number of participants, Spearman's correlation coefficient was used to examine possible influences in observation time and execution time on participants' performances. At least, we assumed a longer observation time leads to lower deviations to each turning point of the route, because more information could be gained from environmental properties

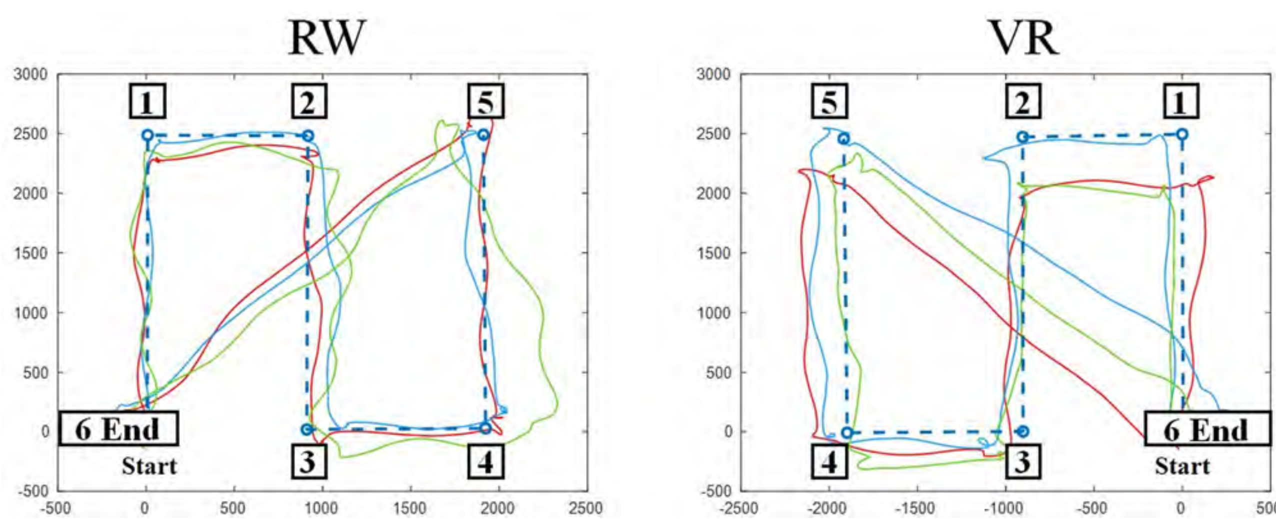


**FIGURE 6.** The bird's eye perspective of the routes (—). Left the real-world route (RW) is presented and on the right side, the participant's pathway in VR is shown. The numbers indicate the turning points of the participants. The turning points were used for the comparison between real and virtual environment. The best three trials in each condition were chosen for visualization.

(scale and depth perception). The results showed no significant correlation between each turning point of the route to the observation and execution time in RW and VR ($p>.05$). Generally, the observation time (s) in VR ($M=26.87$, $SD=0.84$) was higher in comparison to those in RW ($M=20.21$, $SD=1.16$). A Wilcoxon signed-rank test indicated that this difference was statistically significant ($T=73$, $z = -2.667$, $p< .05$). The mean values for the execution time did not differ between the conditions ($T=43$, $z = -0.966$, $p = .334$).

### Discussion

In study 2 (route recall), the main goal of returning back to the start position was equally completed by the participants. The middle part of the route was passed significantly worse in VR compared to RW. Generally, once can be said that walking pathways in VR seem to vary much more in comparison to those from real-world (see. Figure 6). Nevertheless, further statistical analyses have shown significant differences for position 3 and 4 between the conditions. The route was presented via white lines on the ground (see Figure 5). The lengths of the lines were coordinated with the distances given in study 1 to eliminate different distance estimations as a possible influence on participants' performances. The given route on the floor was observed from one static perspective. Without any physical interaction, distance estimates may be challenging for the participants. Therefore, changing the observing perspectives to acquire more spatial information before the participants navigate themselves should be beneficial to their performance. For the next step, to investigate whether solely the visual information could help the participants achieve the same level of spatial navigation, it may be useful to let the participants walk through the route with visual feedback, as in contrast to the study in (Notarnicola et al., 2014), which only provided auditory feedback for the participants. A significant higher performance of the participant can be expected through active exploration in wayfinding task (Cao et al., 2019). It must be considered that in our daily life humans are getting permanent visual feedback. This experiment did not represent a realistic scenario. The extraction of required information by using only the visual cues in each condition was focused and tested. In addition, this test focused more on the examination of the egocentric reference system (Wolbers & Hegarty, 2010). To include factors that rely on the environmental reference system, objects needs to be included or the perspective of route observation must be changed. The results have shown that the participants were able to get back to the starting position to equal extents in both conditions. Major deviations were detected in the middle part of the route in VR (positions 3 and 4). The participants were instructed to follow the route until the end (position 5) and subsequently turn back to the starting position. Perhaps, they were more concentrated on the given task demands in VR, because they felt more uncomfortable or unfamiliar in the virtual environment. Turning back to the original starting position was declared as the most important factor of the task, and therefore, position 5 (the end of the route) and the starting point was primarily in the focus of the participants. Anyway, being disorientated in the middle part of the route did not seem to have any impact on returning to the starting position. Since all participants underwent the tests in both conditions (RW and VR), the memory performance is not meaningful for the comparison of both conditions. Otherwise, a learning effect from the condition in which the test was taken first could be transferred to the other. This learning effect was reduced by creating a mirrored route pathway. The order of conditions was also switched for each participant. Further investigations should compare this possible affectation. A further interesting point is a possible affectation of time on the participants' performances. This could be manipulated by changing the instructions, to let them pass the route as fast as possible after the same observation time. The duration of observation and execution seems to have no affectation in participants' performances. A reason could be that the time differences in observation and execution were too low for having an impact on performance. The main purpose was to compare the time factor between the conditions and whether an impact on performances could be detected similarly in both conditions. An explanation of differences between positions 3 and 4 in RW and VR could be different durations in observation time since we did not measure those for each turning point individually.

Due to the permanent visual perception of our own body in daily life, it was not possible to investigate whether the presence or absence of certain body parts would influence the performance of sports. However, with the help of VR technology, it is manageable to design a study to understand which body parts may play an important role in different sports and the results shall be valuable for improving the current training methods and enhancing the performance.

## Limitation

The length of the data transmission cable and the available tracking distance of the first-generation HTC Vive limited the area used in this article (here $5 \times 5$ m). In future studies, a wireless adapter for the HMD should be considered to resolve the problem of the small tracking area and it may allow the participants to perform more complicated tasks in the sport context. Furthermore, larger distances that play a role in sports can be estimated by the participants and provide further insights into human perception in VR.

In the second study, only the distances (averaged deviations) were evaluated as results. The turning angle of each corner should be evaluated as well in order to see if a compensation of the turning angle exists at each corner. In addition, the participants were allowed to observe the environment only from one specific perspective. In following, multiple observing perspectives or a free observation should be implemented to enhance the performance of the participants. Moreover, the self-created orientation test related to Notarnicola et al. (2014) may have some limitations. First of all, we chose the best trial from each participant due to the sufficient reliability of the data set. If we had chosen the average of the trials, we should have let the participants pass the route more than just three times to make more reliable and valid results. The observation time should have been standardized to exclude a possible impact on participants' performances. Since the participants did not only follow the route for example by hearing the commands given by the experimenter, they also should memorize each turning point. We did not include a memory test in the current study. Participants' ability to remember each turning point may differ individually.

## Conclusion

This paper preliminarily found that the spatial orientation skill is similar in VR and in the RW. To walk different distances and to estimate them verbally could be assessed equally well in RW and VR. The results showed that a more detailed environment with more room features and a higher developed HMD was not necessary to complete this task. The route recreation task was also successfully performed by the participants with minor exceptions. We should emphasize that only a small part of the complex construct of spatial orientation was examined in the current study. Orientating in the real or virtual environment requires more components such as perceiving information from multiple sensory cues, maintaining in short- and long-term memory, or visualization of the own body. Those factors were not analyzed in the current study, but they are helping us in the successful completion of daily tasks. VR is an excellent tool to create any virtual environments with their specific properties, whose purpose could be any training scenarios regarding spatial orientation. If training scenarios in VR should take place in sports, further analyzes with active movements or interactions with objects have to be done, that VR emerges as a valid training method.

## Disclosure statement

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**A.3** Comparison of spatial orientation skill between real and virtual environment

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Virtual Reality
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ORIGINAL ARTICLE

# Comparison of spatial orientation skill between real and virtual environment

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**Abstract**
Virtual reality (VR) is a promising tool and is increasingly used in many different fields, in which virtual walking can be generalized through detailed modeling of the physical environment such as in sports science, medicine and furthermore. However, the visualization of a virtual environment using a head-mounted display (HMD) differs compared to reality, and it is still not clear whether the visual perception works equally within VR. The purpose of the current study is to compare the spatial orientation between real world (RW) and VR. Therefore, the participants had to walk blindfolded to different placed objects in a real and virtual environment, which did not differ in physical properties. They were equipped with passive markers to track the position of the back of their hand, which was used to specify each object's location. The first task was to walk blindfolded from one starting position to different placed sport-specific objects requiring different degrees of rotation after observing them for 15 s (0°, 45°, 180°, and 225°). The three-way ANOVA with repeated measurements indicated no significant difference between RW and VR within the different degrees of rotation ($p > 0.05$). In addition, the participants were asked to walk blindfolded three times from a new starting position to two objects, which were ordered differently during the conditions. Except for one case, no significant differences in the pathways between RW and VR were found ($p > 0.05$). This study supports that the use of VR ensures similar behavior of the participants compared to real-world interactions and its authorization of use.

**Keywords** Virtual reality · Spatial orientation · Visual perception · Head-mounted display

## 1 Introduction

In recent years, virtual reality (VR) has been increasingly used for a lot of purposes, e.g., rehabilitation for people with impaired vision (Palieri et al. 2018), sports training (Pastel et al. 2020a, b, c; Petri et al. 2018, 2019) or therapy for anxiety disorders (Powers and Emmelkamp 2008). The use of VR is not only restricted to entertainment, but also integrated into science due to its enormous advantages. The VR applications allow a user to explore large virtual environments in a smaller physical space (Hirt et al. 2018). Advanced computer technology enables to use realistic computer-generated virtual environments for having a greater degree of control and offers less physically demanding experiences (Kimura et al. 2017). It also provides the potential to increase the motivation of children (Harris and Reid 2005), or when it comes to enhance learning (Sattar et al. 2019).

A factor that has an impact on the quality of perceiving virtual environments is what kind of VR application is used since they differ in the sense of being present in the virtual environment. A head-mounted display (HMD) is known for an increased feeling of being present and for providing high immersion compared to other applications (Mondellini et al. 2018). Since the majority of the population is not familiar with wearing the HMD, physical discomfort, better known as cybersickness, may occur. This could affect the feeling of being present (Mondellini et al. 2018; Witmer and Singer 1998). An established method to measure cybersickness is the simulator sickness questionnaire (SSQ) (Kennedy et al. 1993), which was used in numerous studies (e.g., Christensen et al. 2018; Tregillus et al. 2017; Walch et al. 2017).

Spatial orientation skill should not be reduced to only one ability. Generally, spatial orientation skill allows us to determine our location in relation to the environment

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(Carbonell-Carrera and Saorin 2018). It is also known as the ability to remain oriented in a spatial environment when the objects in this environment are observed from different positions (Fleishman and Dusek 1971). Wolbers and Hegarty (2010) gave a good impression of all included components that ensure spatial orientation. The authors stated the ability to find one's way that involved basic perceptual and memory-related processes are seen as a complex construct due to the multisensory process in which information needs to be adjusted over space and time (Wolbers and Hegarty 2010). The correlation between the spatial orientation and memory is shown in a study in which deficits of them are known as an early marker for pathological cognitive declines (Flanagin et al. 2019). Therefore, different tests were used to analyze spatial memory by letting the participants conduct a test that required them to memorize the order of objects on a map and to reconstruct it from memory (Lehnung et al. 1998). Besides, a lot of studies focused on spatial navigation which is defined as the ability to find the way between places in the environment (Bruder et al. 2012; Diersch and Wolbers 2019). The participants were often asked to complete wayfinding- or homing in tasks, which is essential in our daily life (Cao et al. 2019; Ishikawa 2019; Kitchin 1994). During those tasks, the user perceives the space and acquires spatial knowledge and orientation about it (Carbonell-Carrera and Saorin 2018). The user develops a cognitive map, which is defined as the internal cartographic representation of the surrounding environment (Carbonell-Carrera and Saorin 2018). An additional factor of helping us to orientate in an unknown environment is the distance perception. The comparisons of the perceived distances in VR to the real environment were already examined by letting the participants estimate verbally and by walking different distances using a head-mounted display, which showed no significant differences between both conditions, or at least tendencies of equal estimations (Kelly et al. 2017). Since we used a successor system of the HTC Vive (the HTC Vive pro, Taiwan), distance estimation was not considered in the current study due to already proven equal estimations for egocentric perception. The egocentric reference systems specify location and orientation relative to the observer, whereas the allocentric reference frame works independently of it (Wolbers and Wiener 2014). Previous studies showed that allocentric information is used for coding targets for memory-guided reaching in depth (Klinghammer et al. 2016). The authors emphasized the meaning of both reference systems but also referred to studies that crystallized the egocentric reference system as the dominant role to specify objects' locations (Battaglia-Mayer et al. 2003; Klatzky 1998). For measuring environmental spatial abilities, pointing is a commonly used method that can be varied to examine different aspects of spatial ability (Flanagin et al. 2019; Kimura et al. 2017). Kimura et al. (2017) found out that participants could reorient by using either the geometry of the room or the implemented features (objects), whereas feature-based cues seem to have more impact on spatial ability skills in virtual environments. Previous research has shown that allocentric information was used for memory-guided reaching in depth (Klinghammer et al. 2016).

Despite its development due to higher computing power and practicable applications, it is still unknown whether information processing occurs similarly in RW and VR. Only a few studies have investigated whether the visual perception works equally in VR compared to RW (Pastel et al. 2020a, b, c), although the visualization of the VR environment took place artificially. The visual system relies on the distance and depth indicators which helps us to determine objects in a virtual scene (Ghinea et al. 2018). Most studies considered spatial navigation due to its high relevance in our daily life. Furthermore, pointing was frequently used to measure the ability to orientate in a new environment. During sports, it is important to move precisely to defend the opponent's attacks, to build up an imagination of the position of each teammate, or to grasp appropriated objects such as a ball or racket. When it comes to adequate training in VR, it should be ensured that those skills can be realized in the same way as it works under reality condition without seeing the whole body, as it was the case in other studies (Kimura et al. 2017; Petri et al. 2018).

The aim of the study was to compare the ability to orientate in a new environment by letting the participants move to different sport-specific objects in a real and virtual environment. The focus was to examine whether the participants were able to move actively to each object without using other locomotion technique such as teleportation or cyberwalk (Brewster et al. 2019; Souman et al. 2011). Therefore, two main tasks were developed to examine the spatial orientation skills by first letting the participants walk blindfolded to different placed objects including different degrees of rotation (rotation task). In the second task, they had to walk blindfolded to a previously announced order of objects to observe free movement under more complex conditions (pathway task). Due to the repeated task demands, possible habituation leading to improved performances was examined in the rotation task (first and second run). More co-factors have been chosen to examine, which can have an impact on the participants' performances, such as memory, previous experiences in VR and time for completion the tasks. Other studies reported that user characteristics such as cognitive abilities can have an impact on spatial orientation (Coughlan et al. 2018; León et al. 2016). At present, the rising computing power leads to more realistic graphics and the perception of virtual environments aligns to natural scenes. Nevertheless, based on conflicting research findings, the comparison of the spatial orientation between the virtual and real environment should be further examined.

## 2 Methods

A within-subject-study was designed and conducted under the declaration of Helsinki. The approval of the Ethics Committee of the Otto-von-Guericke University at the Medical Faculty and University Hospital Magdeburg was obtained under the number 132/16.

### 2.1 Experimental apparatus

#### 2.1.1 Hardware

An HTC Vive (HTC, Taiwan) was used with a field of view of 110° (a total resolution of 2880 × 1600 Pixel) for visualization of the virtual environment. To execute the VR environment smoothly, a high-performance desktop equipped with Intel i7 CPU, 16 GB memory, 512 GB SSD, and Nvidia GTX 1080 8GB graphics card was used. A motion capture system (Vicon, Oxford, UK) including 13 cameras with a sampling rate of 200 Hz was used to capture the location of each marker accurately. The VR-controller (HTC Vive) was used to match the position of the virtual objects with those from reality.

#### 2.1.2 Software

The creation of a VR environment with high fidelity preventing the participants from a conflict between the real-world and the virtual environment was created with Blender using the scales and the textures of the objects in the real world. The same room was also used during the experiment in the real environment (see Fig. 1). The created virtual environments were then imported into Unity3D (version 2019.1), and the SteamVR (version 2.5) was used to enable users to interact in the virtual reality. Visual Studio 2017 was used for implementing the C# program for Unity to control the studies.

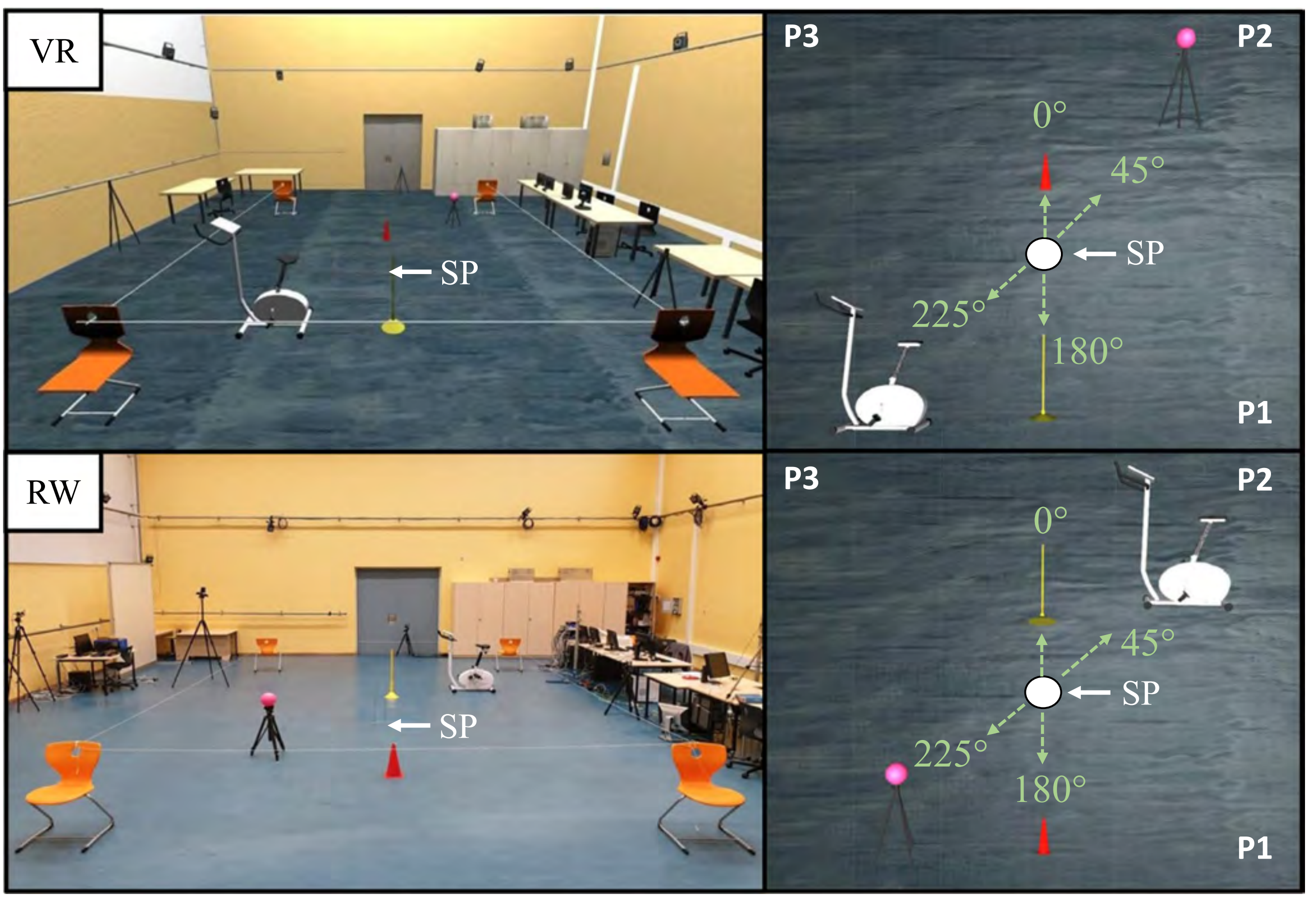


**Fig. 1** Overview of the experimental setup of the orientation test in RW and VR. The order of the objects varied between RW and VR. The rope was placed to fix the area where the participants completed the tasks. The white arrow indicates the starting position. On the right side, the degrees of rotation were presented from the bird's perspective. For better visualization, the objects were rotated 90 degree of the horizontal axis. SP means starting position. P1, P2 and P3 indicate the varied position, from which the participants should walk with a blindfold to the different order of objects (see Table 1) in the pathway task

The raw data were captured and prepared with Vicon Nexus (version 2.4, Oxford, UK). The results of the studies in the next section were processed and calculated with MATLAB R2019a. Finally, statistical analyses were performed with SPSS ($\alpha$=0.05), and the relevant and detailed statistical methods are explained later.

#### 2.1.3 Participants and experimental setup

Twenty young and healthy adults (8 males and 12 females, averaged age = 23.1 ± 3.32 years) were recruited in this study. 10 participants stated having previous experiences of immersion in virtual environments. Previous experiences in VR consisted of the participation of other VR-studies, but no one possessed or owned VR-application for private uses. The study was done in a test room (see Fig. 1) equipped with a Vicon system as described previously. In the middle of the test room, an area was marked with a white rope that was placed between four chairs to ensure sensory feedback for the participants during blindfolded walking. During the experiment, all tasks were conducted by the participants in this fixed area (5.5 m × 7.5 m). Inside the area, the four different objects (a red pylon, a pink ball, a yellow slalom pole, and a white ergometer) were placed also on fixed positions in the test room. The objects in VR were placed via a controller with a programmed function at the same coordinates of the placed objects in the real environment. As perceivable in Fig. 1, the position of each object was switched, when the condition (RW or VR) changed. This reduced the learning process, which could occur due to each participant completing every task in both real and virtual environment on the same day. The distances and the required degrees of rotation remained the same. Six reflective markers, one on the sternum, two at the center of each scapular, one was placed orthogonally of the glenoid cavity from the shoulder, one at the back of the hand right next to the joint of the index finger (this marker was used for the calculation of the deviations later) and a further one on the elbow on the participants to capture movement coordinates using the Vicon system.

### 2.2 Procedure

Before the conduction of the experiments started, the participants agreed and signed the consent form and then filled in a questionnaire regarding their previous experience in the VR, including VR gaming, immersive 360-degree movies, or other relevant applications. After the questionnaires were filled out, the experimenter explained the whole experimental procedure and measured the participants' interpupillary distance to have a clear visual input from the HMD. Each participant completed the experiment in both conditions, but the order was randomized. Before starting the experiment, the participant had to go through the first memory and orientation test. For memory, ten words were observed by the participants for one minute. Afterward, they performed the orientation test (part of the Berliner-intelligence-structure test—BIS), which consisted of an observation phase (90 s observation of black colored buildings from a bird's eye perspective). On the next step, the participants received the same sheet without colored buildings. The task was to mark all previously colored buildings they could remember. Afterward, the participant was asked to reproduce all words named in the memory test. The words were then repeated at the end of the study.

When all preliminary tests were completed, the participants were guided to the starting position (SP) as shown in Fig. 1 and received further instructions. The first task was the rotation task (RT). Each object was observed for 15 s from the SP. Thereafter, the visual scene was darkened in VR and in RW their eyes were covered with a blindfold. The participants should then walk to the object by using the marker placed at the back of their hand right next to their joint of the index finger as reference. Afterward, the participants were guided back to the SP without getting any feedback about their performances. The visual scene was presented again to observe the next object, which was placed at a different degree of rotation in the room (see Fig. 1). Each object should be approached only once.

After the RT, the participants in RW had their blindfolds removed and in VR the visual scene became visible again. The participants then had 2 min observation phase in which they could walk without covered vision through the whole scene to gain further experience with the environment. Then, they had to return to the SP and the vision was covered again (Fig. 1). Afterward, they were guided to a new position (P1, P2, P3) from where they had to walk blindfolded to a previously announced order of objects (e.g., first to the ball and second to the ergometer). This task was referred to as the pathway task (PT). A total of three pathways including two minutes previously conducted observation phases were performed. For each pathway, the participants walked to two objects (Table 1).

The last task was again the first task that required to walk to objects including different degrees of rotation for measuring possible habituation (see Fig. 2). After completing all tasks in both environments, the 10 words at the beginning of the study were queried again. After the tasks were done in VR, the SSQ was handed over. When the experiment was finished, the participants were asked to fill out a self-created questionnaire about used strategies. To obtain the subjective estimated difficulty of each task across the conditions (RW and VR), a scale was used from 0 points (no subjective difficulty) to 10 points (very difficult).

**Table 1** The order of objects the participants had to walk with a blindfold within each condition (RW and VR) in the pathway task

| | Real world (RW) | | | | Virtual reality (VR) | | | |
|---|---|---|---|---|---|---|---|---|
| | First | Second | Third | Fourth | First | Second | Third | Fourth |
| Pathway 1 | SP | P2 | Ball | Ergometer | SP | P1 | Pylon | Bar |
| Pathway 2 | SP | P3 | Pylon | Ergometer | SP | P2 | Ergometer | Ball |
| Pathway 3 | SP | P1 | Bar | Pylon | SP | P3 | Bar | Ball |
| | guided by the investigator | | | guided by the investigator | | | | |

The investigator guided the participants from the starting position (SP) to the perspective (P1, P2, respectively, P3) dependent on the pathway (for better imagination see Fig. 1). From P, they should walk without guidance to the previously mentioned order of objects

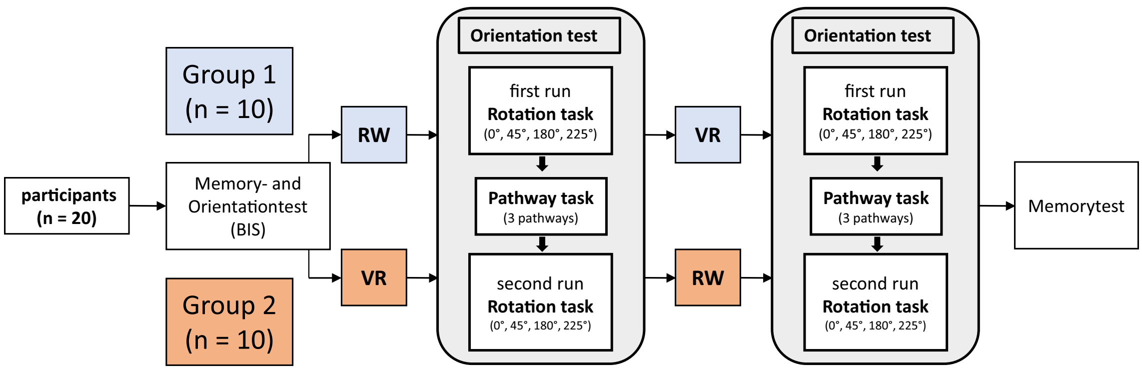


**Fig. 2** Overview of the crossover study design. The grey boxes indicate the orientation tests. Between each pathway completion, there was a two minutes observation phase, in which the participants could walk freely through the environment without covered vision. Group 1 (bright colored) started to complete each task in real world (RW), whereas group 2 began within virtual reality (VR) (dark colored)

### 2.2.1 Data analysis

The quality of the orientation to the objects was measured by the two-dimensional deviation (cm) of the marker which was placed on the back of the hand right next to the joint of the index finger on the preferred hand to the real position of each object. In addition, the time (seconds) from the starting position (or changed perspective for the pathways) until the participant reached the object was captured. The deviations were calculated by using a MATLAB script for the rotation and pathway task. The dataset was checked for the requirements of the statistical analysis (normal distributions, no significant outliers, and given sphericity). Effect sizes were obtained using Cohen's $f$ being defined as $f = 0.1$ small effect, $f = 0.25$ moderate effect, and $f = 0.4$ large effect (Cohen 2013, pp. 285–287). SPSS, version 25, was used to run the statistics. To detect memory skills, a Wilcoxon signed-rank test was used to reveal possible differences in remembering the listed words and the buildings. To determine the correlation coefficient between the memory skills and the accurate walking (distance to the objects in cm) exists, the spearman rank correlation was used due to the small sample size and non-parametric data. This was also done for the analysis of correlations between RW and VR including the RT and PT. The level of significance was set to $\alpha = 0.05$.

## 2.3 Rotation task (RT)

For the comparisons between the deviations (cm), time for completion (time in seconds) and subjective estimation of difficulty, which all define the dependent variable, a three-way ANOVA with repeated measurements with degrees of rotation [0°, 45°, 180°, 225°], the conditions [RW, VR], and the runs [first, second] was conducted. If sphericity was not given, the Greenhouse-Geisser corrected data were chosen for analyses. Although non-parametric data set was given in some cases, we chose to conduct the ANOVA since previous studies showed the robustness in terms of power and violations of normality by considering the distribution of skewness and kurtosis (Blanca et al. 2017). Dunn-Bonferroni corrected post-hoc tests were used to determine the pairwise comparisons within the different placed objects. Significant outliers were removed using boxplot (participant 12 and 17).

### 2.4 Pathway task (PT)

For the pathways, participant 14 was removed from the data set due to technical problems. Due to normal distributed data and given sphericity, a two-way ANOVA with repeated measurements was conducted. Furthermore, Dunn-Bonferroni corrected post-hoc tests were used to analyze the pairwise comparisons using the corrected significance to avoid the alpha error accumulation. Similar to the first task, the dependent variables were deviation (cm), subjective estimation of difficulty (0 points = no subjective difficulty to 10 points = very difficult) and for time completion (time in seconds), whereas the pathways (three in each condition) were treated as independent variable.

We compared the performances of the participants between the conditions (RW and VR). In addition, an analysis within each condition was made to get supportive information about similar behavior in both environments independently. The comparison of the first and the second run of the RT allows us to examine possible habituation to the task demands in both conditions. The first step was to examine whether habituation from the starting condition to the following one occurred. This step was completed first to exclude possible learning from one condition to the following. After that, further analyses with the associated factors were conducted.

## 3 Results

The results are divided into two parts. The first part focuses on the comparison of the performances within and between each condition (RW and VR) by comparing the deviations (measured in cm) and time for completions (s) for the rotation task and pathway task. The second part describes the analysis of the memory skills and orientation skills (BIS), and the subjective estimation of difficulty. Before starting with the analysis, it was examined whether there occurred differences from the starting and the subsequent condition. No significant differences were found between the starting condition and the following one for all dependent variables [deviations in cm, time for completion in s, subjective estimation of difficulties] neither within the rotation nor for the pathway task ($p > 0.05$). This was done before to be able to focus on the comparison of both conditions afterward. In addition, two runs were made within the rotation task, and the analysis within and between each condition was made separately.

### 3.1 Rotation task

The deviation (cm), time for completion (s), and subjective estimation (1–10) of difficulty in the rotation task are presented in Tables 2, 3, and 4.

For the deviations, no significant differences were found between the conditions (RW and VR) and the runs (first and second run). The results indicate significant differences within the deviations of the different placed objects that needed different degrees of rotation. The participants walked most accurately to the object requiring no rotation (in RW the bar and in VR the pylon). The other objects were reached in the same manner in both conditions. Participants needed more time to walk to objects that required increased rotations in both conditions. Similar to the deviations within accuracy, the most differences were shown between the object that required no rotation in comparison with the others. This is observable in both conditions. No significant differences were found between the first and the second run for each rotation ($p > 0.05$). An overview of the estimations of difficulty is given in Table 4. Generally, no differences were detected between RW and VR for each degree of rotation in each run ($p > 0.05$). For all rotation degrees existed no significant differences between the first and the second run in both conditions ($p > 0.05$). The objects which required less rotation were subjectively easier to reach than the others. In VR, the participants specified higher difficulty to complete the tasks. However, those differences were not significant ($p > 0.05$).

The comparison of the different rotations showed that the participants estimated the task as more difficult when the degree of rotation increased (see Table 4). This is shown by an increased effect size, e.g., when the first object which required no rotation was compared to the last object required a 225° rotation (Fig. 1).

### 3.2 Pathways

The results of the pathways indicate no significant difference between the RW and VR for the deviations, time for completion and subjective estimation of difficulty (see Table 5). For pathway 2, the participants needed significantly more time to reach the end compared to the others. However, this had a greater impact in RW than in VR.

### 3.3 Simulator of sickness

The results of the SSQ showed high values for nausea (11.45 ± 12.61), oculomotor (18.95 ± 14.02) and for disorientation (20.88 ± 19.43). The overall average value was 19.45. Previous research (Stanney et al. 1997) stated negligible symptoms lower than 5, minimal (5–10), significant (10 to 15), concerning (15 to 20), and worst-case and not appropriated simulator (higher than 20). However, the participants did not complain about any symptoms nor did they criticize the VR-environment. The participants mostly complained about not given feedback, which made it hard to estimate their accomplishments. Only one participant complained

**Table 2** Comparison of the deviations between the marker placed on the back of the preferred hand to the objects required different rotations

| | Deviations in cm | | 0° | 45° | 180° | 225° |
|---|---|---|---|---|---|---|
| First run ($n=18$) | RW | $M+$SD (in cm) | 24.5 ± 12.3 | 50.0 ± 19.5 | 40.3 ± 25.0 | 50.0 ± 43.4 |
| | VR | $M+$SD (in cm) | 29.4 ± 21.6 | 52.2 ± 25.3 | 43.0 ± 23.6 | 58.8 ± 29.9 |
| Second run ($n=18$) | RW | $M+$SD (in cm) | 20.3 ± 8.8 | 57.1 ± 45.2 | 52.7 ± 33.8 | 55.6 ± 29.1 |
| | VR | $M+$SD (in cm) | 21.5 ± 11.4 | 39.3 ± 21.1 | 45.1 ± 32.3 | 50.0 ± 33.3 |

| Factor | df, error, $F$ value, $p$ value, eta-quadrat, effect size | Bonferroni corrected post-hoc comparisons revealed significant differences (RW and VR) |
|---|---|---|
| *Three-way ANOVA with repeated measurements and calculated effect sizes* | | |
| Degrees of rotation | $F(2.025, 34.433)=16.584$, $p<0.001$, $\eta_p^2=0.494$ (effect size = 0.56, large effect) | 0°–45° ($p<0.001$) RW |
| | | 0°–180° ($p<0.001$) RW, VR |
| | | 0°–225° ($p<0.001$) RW, VR |
| Condition (RW vs. VR) | $F(1, 17)=0.144$, $p=0.709$, $\eta_p^2=.008$ (effect size = 0.08, small effect) | No significant difference between RW and VR was found |
| Runs | $F(1, 17)=0.83$, $p=0.777$, $\eta_p^2=.005$ (effect size = 0.05, small effect) | No significant difference between the first and the second run was found |
| Degrees of rotation * Condition (RW vs. VR) | $F(3, 51)=0.460$, $p=0.711$, $\eta_p^2=.026$ (effect size = 0.02, small effect) | No significant interaction effects were found concerning the degrees of rotation and conditions within the deviations |

The number of participants is given by $n$. The three-way ANOVA was performed with the depended variable (deviations in cm) as the outcome and the factors rotation degree [0°, 45°, 180°, 225°], condition [RW, VR] and runs [first, second] were included. The level of significance was set to $\alpha=0.05$. Effect sizes were obtained using Cohen's $f$ being defined as $f=0.1$–0.25 small effect, $f=0.25$–0.4 moderate effect, and $f=0.4$ large effect. The examination of the degrees of rotation was extended by using Bonferroni-corrected post-hoc comparisons to reveal where the differences are. Those differences are related to RW and VR since the same occurred within both conditions. The asterisk indicates the interaction between two factors

about dizziness due to a lost signal from the lighthouses to the HMD which was normally not the case. Four participants appeared to perceive smaller distances and decreased objects' sizes in VR compared to RW, but this did not affect the physical discomfort.

### 3.4 Memory

No significant differences were found after the first and second-time points in the numbers of remembered words ($p>0.05$). A high significant correlation between the results of the short-term and long-term memory test was found ($r = 0.81$, $p < 0.01$, $N = 20$). No significant correlations were found between the test of remembering the buildings and the short-term memory ($r = 0.16$, $p = 0.954$, $N = 20$) and for long-term memory testing ($r = 0.088$, $p = 0.711$, $N = 20$). The ability to memorize the number of words did not influence the remembering of marked buildings from the birds-eye perspective. No significant correlations were found between the memorizing ability (neither for the words nor for the remembered buildings) and the accuracy of reaching the objects neither for the rotations nor for the pathways ($p > 0.05$).

## 4 Discussion

The goal of this study was to compare the ability to orientate in a virtual and real environment towards different placed objects. To check whether the participants differed in terms of accuracy (cm), they were equipped with markers to trace their positions in a two-dimensional space. The sport-specific objects were placed in positions that required different degrees of rotation to reach them blindfolded. In addition, the starting position varied, and the participants then had to walk blindfolded to a different order of objects. The two-dimensional deviation was captured and calculated for the degrees of rotation and for each pathway the participants had to walk. The results are divided into two main parts. The first part concentrates on the ability to rotate within RW and VR (rotation task). The second part shows whether the participants were able to memorize each object in each

**Table 3** Comparison of the time for completion (s) in the rotation task

| | Time for completion | | 0° | 45° | 180° | 225° |
|---|---|---|---|---|---|---|
| First run ($n=18$) | RW | $M+SD$ (in cm) | 5.8 ± 1.3 | 9.4 ± 2.6 | 10.4 ± 2.7 | 11.1 ± 3.1 |
| | VR | $M+SD$ (in cm) | 7.2 ± 2.1 | 8.1 ± 2.0 | 10.8 ± 3.5 | 11.0 ± 2.5 |
| Second run ($n=18$) | RW | $M+SD$ (in cm) | 5.8 ± 2.2 | 9.2 ± 2.9 | 9.7 ± 2.6 | 11.1 ± 4.9 |
| | VR | $M+SD$ (in cm) | 5.5 ± 1.7 | 8.3 ± 2.7 | 10.4 ± 3.3 | 11.0 ± 3.0 |
| Factor | | *df*, error, *F* value, *p* value, eta-quadrat, effect size | | Bonferroni corrected post-hoc comparisons revealed significant differences (RW and VR) | | |
| *Three-way ANOVA with repeated measurements and calculated effect sizes* | | | | | | |
| Degrees of rotation | | $F(3, 51)=50.095$, $p<0.001$, $\eta_p^2=0.747$ (effect size = 1.12, large effect) | | 0°–45° ($p<0.001$) RW, VR | | |
| | | | | 0°–180° ($p<0.001$) RW, VR | | |
| | | | | 0°–225° ($p<0.001$) RW, VR | | |
| | | | | 45°–180° ($p<0.05$) VR | | |
| | | | | 45°–225° ($p<.05$) VR | | |
| Condition (RW vs. VR) | | $F(1, 17)=0.003$, $p=0.958$, $\eta_p^2=.001$ (effect size = 0.01, small effect) | | No significant difference between RW and VR was found | | |
| Runs | | $F(1, 17)=1.015$, $p=0.328$, $\eta_p^2=.056$ (effect size = 0.05, small effect) | | No significant difference between the first and the second run was found | | |
| Degrees of rotation* condition (RW vs. VR) | | $F(3, 51)=4.930$, $p=0.004$, $\eta_p^2=.225$ (effect size = 0.23, small effect) | | Small differences occur between RW and VR concerning the interaction effects between degree of rotation and condition within the time for completion | | |

The number of participants is given by n. The three-way ANOVA was performed with the depended variable (deviations in cm) as the outcome and the factors rotation degree [0°, 45°, 180°, 225°], condition [RW, VR] and runs [first, second] were included. The level of significance was set to $\alpha=0.05$. Effect sizes were obtained using Cohen's *f* being defined as $f=0.1$–$0.25$ small effect, $f=0.25$–$0.4$ moderate effect, and $f=0.4$ large effect. The examination of the degrees of rotation was extended by using Bonferroni-corrected post-hoc comparisons to reveal where the differences are. The asterisk indicates the interaction between two factors

condition by walking to two objects as accurately as possible in a specific order (pathway task). In both tasks, the two-dimensional deviations (cm), the time for completion, and the subjective estimation of difficulty were treated as the dependent variable, and they were defined as parameters revealing the quality of spatial orientation skills within both conditions. Furthermore, we used the SSQ to test whether the VR simulation impacted participants' state of mind. We also examined possible correlations between memory and orientation skills.

Although doubts about using the HTC Vive for scientific use still exists (Niehorster et al. 2017), the results showed no significant differences between RW and VR in the two-dimensional deviations of the objects that required different degrees of rotation (0°, 45°, 180°, and 225°). A closer look revealed differences from object 1 (required no rotation, 0°) to the other placed objects (see Table 2). The extent of rotation had predominantly no impact on the ability to rotate in both conditions (see Tables 2, 3, and 4). The same observed quality of walking including different degrees of rotation in both conditions endorses that the perception of the environments worked similarly, which is essential for virtual walking (Cirio et al. 2013).

Nevertheless, the ability to orientate was only measured by walking towards the objects and by measuring the two-dimensional distance (in cm). To reveal more information about the ability to rotate between objects, further analysis of the degrees of rotation should be done, such as locomotion trajectories between two oriented points in space (Cirio et al. 2013). Although a higher performance of the participant can be expected due to active exploration in the wayfinding task (Cao et al. 2019), the statistics showed no significant differences between the first and the second run. No habituation occurred after remaining longer in VR or also for RW. Although, the participants found the second run to be easier, no significant differences were found in terms of accuracy (deviations in cm) and pace (time in seconds).

The study did not represent a realistic setting, since normally visual feedback is always present during exploring new environments. The locations of objects are represented

**Table 4** Comparison of the subjective estimation of difficulty in the rotation task

| | Subjective estimation of difficulty | | 0° | 45° | 180° | 225° |
|---|---|---|---|---|---|---|
| First run ($n = 19$) | RW | $M + SD$ (in cm) | $1.8 \pm 1.2$ | $3.1 \pm 1.5$ | $2.8 \pm 1.5$ | $3.5 \pm 1.6$ |
| | VR | $M + SD$ (in cm) | $2.3 \pm 1.5$ | $3.2 \pm 1.7$ | $3.4 \pm 1.6$ | $4.1 \pm 1.9$ |
| Second run ($n = 19$) | RW | $M + SD$ (in cm) | $1.8 \pm 1.0$ | $2.5 \pm 1.1$ | $2.4 \pm 1.3$ | $2.7 \pm 1.2$ |
| | VR | $M + SD$ (in cm) | $1.8 \pm 1.1$ | $2.7 \pm 1.4$ | $2.5 \pm 1.3$ | $2.8 \pm 1.3$ |

| Factor | *df*, error, *F* value, *p* value, eta-quadrat, effect size | Bonferroni corrected post-hoc comparisons revealed significant differences (RW and VR) |
|---|---|---|
| *Three-way ANOVA with repeated measurements and calculated effect sizes* | | |
| Degrees of rotation | $F(1.607, 28.918) = 21.298$, $p < 0.001$, $\eta_p^2 = 0.542$ (effect size = 0.64, large effect) | 0°–45° ($p < 0.001$) RW, VR |
| | | 0°–180° ($p < 0.05$) RW, VR |
| | | 0°–225° ($p < 0.001$) RW, VR |
| | | 180°–225° ($p < 0.001$) RW, VR |
| | | 45°–225° ($p < 0.001$) VR |
| Condition (RW vs. VR) | $F(1, 18) = 2.446$, $p = 0.135$, $\eta_p^2 = .120$ (effect size = 0.12, small effect) | No significant difference between RW and VR was found |
| Runs | $F(1, 18) = 17.532$, $p = 0.001$, $\eta_p^2 = .493$ (effect size = 0.57, large effect) | The second run was found to be easier than the first in both conditions |
| Degrees of rotation* Condition (RW vs. VR) | $F(3, 54) = 0.573$, $p = .636$, $\eta_p^2 = .031$ (effect size = 0.03, small effect) | No significant interaction effects were found concerning the degrees of rotation and conditions within the subjective estimation of difficulty |

The number of participants is given by *n*. The three-way ANOVA was performed with the depended variable (deviations in cm) as the outcome and the factors rotation degree [0°, 45°, 180°, 225°], condition [RW, VR] and runs [first, second] were included. The level of significance was set to $\alpha = 0.05$. Effect sizes were obtained using Cohen's *f* being defined as $f = 0.1$–$0.25$ small effect, $f = 0.25$–$0.4$ moderate effect, and $f = 0.4$ large effect. The examination of the degrees of rotation was extended by using Bonferroni-corrected post-hoc comparisons to reveal where the differences are. The asterisk indicates the interaction between two factors

in egocentric (Thompson and Henriques 2011) and allocentric reference system (Schütz et al. 2015). Both systems are necessary when humans perform memory-guided reaching movements (Byrne and Crawford 2010). The current study included both, since the participants had to observe and simultaneously extract information from the starting position, as well as exploring the scenes by walking through them. Therefore, it is difficult to differentiate between the two reference systems since other studies showed that allocentric information was used in 3D VR to reach out for memorized objects (Klinghammer et al. 2016) and within perceptual tasks (Murgia and Sharkey 2019). We refer to Klinghammer et al. (2016), who gave a good overview of the role of each reference system.

Examining the pathways also revealed no significant differences between RW and VR (see Table 5). Changing the starting position and therefore also changing the perspective led to no significant differences between the conditions in the two-dimensional deviations. Except for one case, no differences of the time needed to complete each pathway were found. The only difference was found within the RW condition. The deviations in the rotation task were less than those from the pathways. The participants stated to have less problems to imagine the position of each object from egocentric perspective. Since no differences in the deviation could be found, it can be assumed that the performance of the basic locomotion tasks was done in a stereotyped manner, which means that the participants followed similar trajectories when walking from object to object (Hicheur et al. 2007).

The subjective estimation of difficulty and time to completion did not deliver surprising results. Higher rotations were estimated more difficult or needed longer to complete in both conditions. This is not consistent with previous studies, which reported that tasks in VR were completed with longer time durations compared to RW (Pastel et al. 2020a, b, c; Read and Saleem 2017). The participants stated verbally to be less accurate or needed more time in VR.

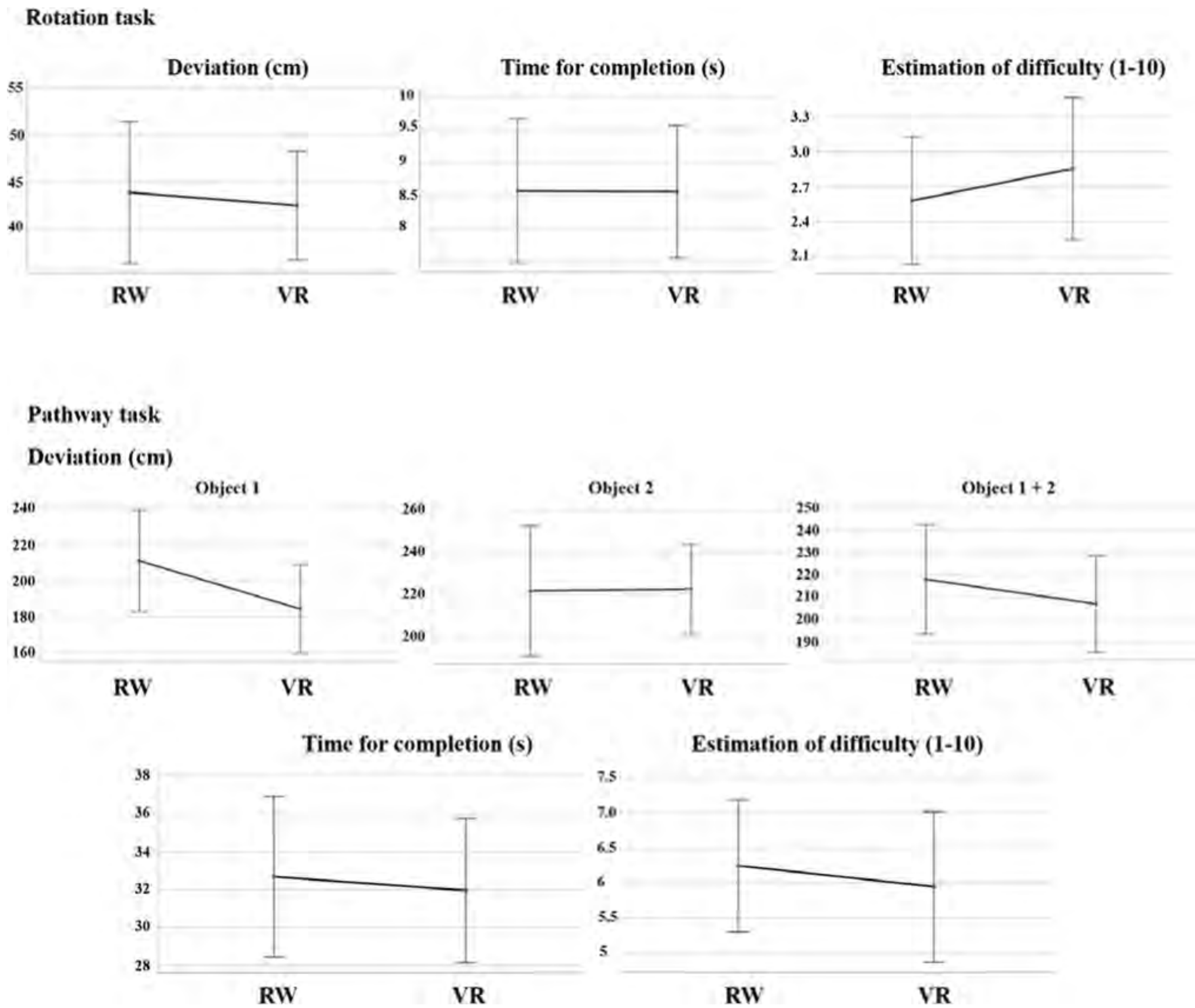


**Fig. 3** RW and VR condition with 95% confidence intervals revealing an overview about the precision of results

However, those differences were not significant between the different degrees of rotation (Table 4) and the different pathways (Table 5) between RW and VR. Those differences were not consistent with other studies, in which tasks completed in VR were rated more difficult (Pastel et al. 2020a, b, c). A reason for that could be the simple task demands of the present study since no complex movements were needed to successfully complete them. The results showed that the bar and the pylon were estimated as the easiest to reach, whereas the ergometer and the ball were rated higher in terms of difficulty.

The task demands consisted of localizing the objects with the marker placed at the back of the hand right next to the joint of the index finger and no vision was provided. This presupposes proprioceptive knowledge to be able to specify an accurate position of the objects. During the observation of the scene between each pathway, no visualization of the subject's own body was provided. Previous studies have shown that this factor could lead to a negative impact on performances (Pastel et al. 2020a, b, c). We ensured that there was no loss in tracking during the observation of the virtual scene due to high shifting in the offset to the physical ground plane (Niehorster et al. 2017). However, the results of this study showed that reaching to an object (grasping the object and associating it to a specific position) could be completed without any restrictions compared to the real condition, also when no whole-body visualization was provided.

Overall, the study showed that VR is a useful tool for analyzing the spatial orientation in VR and the visual input received from the HMD worked equally, which is in line with previous studies (Kimura et al. 2017; Pastel et al.

**Table 5** Comparison of the pathways (P1, P2, P3) between RW and VR

| Deviations | | Pathway 1 (P1) | Pathway 2 (P2) | Pathway 3 (P3) | Two-way ANOVA with repeated measurements and calculated effect sizes | | |
|---|---|---|---|---|---|---|---|
| Object 1 | | | | | Factor | df, error, $F$ value, $p$ value, eta-quadrat, effect size | Bonferroni corrected post-hoc comparisons revealed significant differences |
| Deviation (in cm) $n=19$ | | | | | | | |
| RW | $M+SD$ (in cm) | 203.2 ± 110.0 | 145.6 ± 79.9 | 283.4 ± 85.1 | Pathways | $F(2, 36)=3.213$, $p=.052$, $\eta_p^2=.151$ (effect size = 0.15, small effect) | No differences were found between the pairwise comparisons |
| VR | $M+SD$ (in cm) | 201.3 ± 89.1 | 194.2 ± 129.9 | 157.7 ± 65.6 | Condition | $F(1, 18)=1.853$, $p=.190$, $\eta_p^2=.093$ (effect size = 0.09, small effect) | No significant difference between RW and VR was found |
| Object 2 | | | | | | | |
| Deviation (in cm) $n=20$ | | | | | | | |
| RW | $M+SD$ (in cm) | 233.9 ± 75.4 | 247.3 ± 115.6 | 184.4 ± 149.4 | Pathways | $F(2, 38)=0.416$, $p=.663$, $\eta_p^2=.021$ effect size = 0.21, small effect) | No differences were found between the pairwise comparisons |
| VR | $M+SD$ (in cm) | 209, 6 ± 100.4 | 220.3 ± 74.9 | 237.8 ± 100.0 | Condition | $F(1, 19)=0.003$, $p=.961$, $\eta_p^2=.001$ (effect size = 0.01, small effect) | No significant difference between RW and VR was found |
| Object 1 + Object 2 (n = 20) | | | | | | | |
| Deviation (in cm) | | | | | | | |
| RW | $M+SD$ (in cm) | 221.4 ± 74.4 | 199.9 ± 80.5 | 232.7 ± 98.0 | Pathways | $F(2, 38)=0,516$ $p=.601$, $\eta_p^2=.026$ (effect size = 0.03, small effect) | No differences were found between the pairwise comparisons |
| VR | $M+SD$ (in cm) | 209.6 ± 71.0 | 204.9 ± 89.1 | 206.5 ± 88.0 | Condition | $F(1, 19)=0.608$, $p=.445$, $\eta_p^2=.031$ (effect size = 0.03, small effect) | No significant difference between RW and VR was found |
| Time for completion (in s) ($n=19$) | | | | | | | |
| RW | $M+SD$ (in s) | 32.9 ± 10.5 | 36.6 ± 13.2 | 28.5 ± 7.3 | Pathways | $F(2, 36)=5.891$, $p=0.006$, $\eta_p^2=.247$ (effect size = 0.25, small effect) | P2–P3 ($p<0.05$) |
| VR | $M+SD$ (in s) | 31.5 ± 8.8 | 33.3 ± 8.9 | 31.0 ± 8.9 | Condition | $F(1, 18)=0.426$, $p=0.522$, $\eta_p^2=.023$ (effect size = 0.02, small effect) | No significant difference between RW and VR was found |
| *Subjective estimation of difficulty (n = 19)* | | | | | | | |
| RW | $M+SD$ | 6.1 ± 2.0 | 6.8 ± 2.3 | 5.9 ± 2.0 | Pathways | $F(2, 36)=6.411$, $p=0.004$, $\eta_p^2=.263$ (effect size = 0.27, moderate effect) | P1–P2 ($p<0.05$) |
| VR | $M+SD$ | 5.6 ± 2.0 | 6.2 ± 2.3 | 6.1 ± 2.5 | Condition | $F(1, 18)=0.649$, $p=0.431$, $\eta_p^2=.035$ (effect size = 0.04, small effect) | No significant difference between RW and VR was found |

The number of participants is given by $n$. The two-way ANOVA was performed with the depended variable (deviations in cm, time for completion, subjective estimation of difficulty) as the outcome and the factors rotation degree [P1, P2, P3], condition [RW, VR]. Effect sizes were obtained using Cohen's f being defined as $f=0.1$–$0.25$ small effect, $f=0.25$–$0.4$ moderate effect, and $f=0.4$ large effect

2020a, b, c). Since navigational deficits in cognitive aging or neurodegenerating disease could be found (Cushman et al. 2008; Laczó et al. 2018), further investigations with seniors should be conducted to compare the ability to orientate precisely to objects in a virtual scene.

## 5 Limitation

The current study has its limitation on the transfer on realistic scenarios due to its laboratory setting and standardized conduction. In sports, for example, the accurate movement needs to be done under time pressure and in a more complex scenario including teammates, opponents, field restrictions, and interacting objects (ball, racket, etc.). Besides, the current task demands guided the participants to set the focus only on one feature such as one static object in the rotation task, and stepwise through the pathways, which is also not in line within realistic sports scenarios. During the observation phases, the subject's own body was not visualized which could have had an impact on performances. To form a valid conclusion, more people should be tested to increase the statistical power and to substantiate the equality of RW and VR in terms of spatial skills. Therefore, further excluding criteria concerning the selection of participants should be considered such as experience in VR, gender distribution or the testing time.

## 6 Conclusion

The results of the current study supported the similarity of the ability to reach objects in VR compared to the real environment. Nevertheless, the subjective impression of the virtual environment seems to differ due to graphical limitation and restricted field of view (110°). Regarding the use of VR in sports, more sport-related tasks should be implemented and completed by the participants to verify this tool as a valid and reliable method.

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**Availability of data and material** Yes

**Code availability** Yes

## Declarations

**Conflict of interest** The authors declare that they have no conflict of interest.

**Ethics approval** The approval of the Ethics Committee of the Otto-von-Guericke University at the Medical Faculty and University Hospital Magdeburg was obtained under the number 132/16.

**Consent of participate** Available.

**Consent of publication** All authors agreed for the publication process.



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**A.4** Effects of body visualization on performance in head-mounted display virtual reality

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RESEARCH ARTICLE

# Effects of body visualization on performance in head-mounted display virtual reality

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## Abstract

Although there are many virtual reality (VR) applications in sports, only a handful of studies visualized the whole body. There is still a lack of understanding, how much of the own body must be visualized in the head-mounted display (HMD) based VR, to ensure fidelity and similar performance outcome as in the real-world. In the current study, 20 young and healthy participants completed three tasks in a real and virtual environment: balance task, grasping task, and throwing task with a ball. The aim was to find out the meaning of the visualization of different body parts for the quality of movement execution and to derive future guidelines for virtual body presentation. In addition, a comparison of human performance between reality and VR, with whole-body visualization was made. Focusing on the main goal of the current study, there were differences within the measured parameters due to the visualization of different body parts. In the balance task, the differences within the VR body visualization consisted mainly through no-body visualization (NB) compared to the other visualization types defined as whole-body (WB), WB except feet (NF), as well as WB except feet and legs (NLF). In the grasping task, the different body visualization seemed to have no impact on the participants' performances. In the throwing task, the whole-body visualization led to higher accuracy compared to the other visualization types. Regarding the comparison between the conditions, we found significant differences between reality and VR, which had a large effect on the parameters time for completion in the balance and grasping task, the number of foot strikes on the beam in the balance task, as well as the subjective estimation of the difficulty for all tasks. However, the number of errors and the quality of the performances did not differ significantly. The current study was the first study comparing sports-related tasks in VR and reality with further manipulations (occlusions of body parts) of the virtual body. For studies analyzing perception and sports performance or for VR sports interventions, we recommend the visualization of the whole body in real-time.



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## Introduction

There are many different applications of a head-mounted display (HMD) based virtual reality (VR), but only a few studies integrated a virtual body in the context of sports applications (for review see [1]). Furthermore, VR is a promising tool for expanding the possibilities of psychological and sport training applications due to many aspects in the virtual environment that can be controlled and manipulated, which are not possible in a real-world setting [2]. VR allows for the manipulation of the body representation in terms of structure, size, morphology, and perspective [3, 4]. Skills learned in adequate VR training with proper stimuli can be transferred to a real-world setting (for review see [5]). Previous studies in the field of psychology have shown that a virtual body can increase the feeling of presence and the degree of reality (e.g. [6]), especially when participants are allowed to choose a favorite design [7], and when the virtual body is realistic [8].

Fidelity, that means a simulation, which recreates the real-world system, leads to the users' feel of presence in VR [9]. The authors also described the confusion about terms like fidelity, validity, immersion, and presence and gave a good overview of how to use them in the right context. They also presented different types of fidelity for example the physical one, which refers to the level of realism provided by the simulation. They stated that physical fidelity is important to elicit a feeling of the presence of the participant [9]. An easy and valid approach to assess the strength of the feeling of 'being there' is to use questionnaires (for example see [10, 11]), which used Likert scales to gauge the participants' impression [12]. A further recommendation for testing the presence is to measure physiological responses and behavior for example the stress level measured by increasing skin conductance responses [12]. The sensation of presence, as a psychological, attentional, and cognitive state, is linked to psychological and contextual factors, cognitive and sensorimotor aspects, as well as to visuo-proprioceptive coherency [13]. Therefore, not only a virtual body is needed, but a body, which is accepted by the users. Experiences with the own body also have to match experiences with the virtual body. It is evident, that the body schema is changeable due to the neuroplasticity in the human brain [14]. Good body-ownership (when participants accept and can control the virtual body) also leads to better accuracy in movement tasks [15]. The virtualization of the own body can further be important for distance estimation [16], grasping tasks [17], as well as for the improvement of action control, performance accuracy, and lower limb coordination during obstacle avoidance [18]. For a review of distance estimation in VR, see [19], as well as [20] which showed that different results depend on different measuring methods. However, [13] found that the integration of haptic (vibrotactile) feedback further increases performance in navigation and grasping tasks, and it supports the correct position of virtual body segments by using visual information.

Virtual bodies can be accepted very quickly by the users, and can also be easily controlled, even if these bodies do not match the own body shape or body size, or if the virtual body contains additional body parts (e.g. a tail or [21]). In a review with a focus on rehabilitation, [22] explain the importance of movement visualization for learning progress in VR interventions. In recent reviews, [3] discussed the sense of embodiment, and [23] explained principles of bodily self-consciousness based on recent experiments about imagined body-ownership and rubber hand experiments. Virtual bodies that are different from the own real body (e.g. a body from a child [24]), or from an ethnic minority [25] can also be accepted quickly, and users change their behavior according to the body size, body shape and the social role. Virtual bodies can, therefore, affect perception and behavior [8].

Virtual embodiment is crucial for controlling the VR and communicating with the environment or other virtual characters. [26] demonstrated that humans respected the same behavioral rules (e.g. interpersonal distance) in VR as in the real-world. As well as other behavioral patterns were observed, e.g. men who were shy around women in the real-world were also shy around female virtual characters [26]. However, it is still unknown if humans accept virtual characters as presented humanoid, and if there are any differences in interpersonal behavior between several kinds of characters, e.g. agents controlled by a computer or agents controlled by an other human [27].

At the present time, only a few numbers of studies included the whole-body visualization. In most studies, either nothing of the own body or only some body parts (in most cases the hands for better orientation) were visualized [1]. So far, whole body visualizations in HMD based VR were used for therapy [7] or for investigations of embodiment to analyze the link between central body representations and higher cognitive functions [14, 23]. In sports, the whole body (or body-part) visualizations were utilized to increase the degree of realism, to support spatial navigation, and to decrease symptoms of cybersickness, which can be defined as physical discomfort elicited by the stay in VR. [28] used whole body visualizations in squat movements to examine the influence of such a visualization, as wells as different perspectives on the own motor execution using a virtual mirror. For a review of whole-body motion reconstructions in HMD based VR, we refer to the review of [8]. The tracking of the body in VR applications is an increasing research interest, and for whole-body tracking marker-based, marker-less (in most cases kinect systems), as well as inertial measurement units can be utilized [8]. Whole-body motion tracking in HMD based virtual environments was shown to be beneficial for spatial presence and involvement [29]. Presenting a virtual body in combination with the head-mounted display based virtual reality is crucial to the sense of being in a virtual environment [12].

Generally, one fundamental research question was: to what extent can virtual bodies be perceived as own bodies in a virtual environment [30]. [3] gave an overview of the meaning of embodiment in a virtual environment. The authors emphasized that embodiment is associated with concepts of the sense of self-location, the sense of agency, and the sense of body ownership. Self-location describes the feeling that one feels self-located inside the biological or an avatar´s body. For this, the first-person perspective is crucial, since the feeling of being self-located can be influenced by the origin of the visuospatial-perspective [31, 32]. The sense of agency is present in active movements and results from the predicted sensory consequences of one's actions from the efference copy and the actual sensory consequences [3]. The authors also described the sense of body ownership, which implies that the body is the source of the experienced sensations through a combination of bottom-up and top-down processes. Comparable performances of the participants in a real and virtual environment could be a sign of acceptance of the virtual body as their own. Nevertheless, there is still a lack of understanding in how much of the own body must be visualized in HMD based VR to ensure fidelity and similar performance outcome as in the real-world. This could be important for future training recommendations. There already exist some intervention studies in immersive VR, which showed benefits from such training (e.g. [33–35]) but the transfer into reality is often unresolved (for review see [5]). In addition, there are only a few studies, which compared sports-specific behavior in VR and the real-world (e.g. [35, 36]), for review of ball sports in VR, see [37]. While in karate specific studies, no or only slight differences were found between VR and reality, previous results showed that perception, in general, might be different between both conditions due to different usage of the ventral and dorsal stream for visual information processing [2].

There are only a few studies available that compared the motor behavior between VR and reality. Furthermore, in none of these studies, the influence of different body visualization by occlusion of different body parts was analyzed before. According to [8], there is a further need for whole-body motion reconstruction studies and studies that manipulated such whole-body visualizations. Especially, sports specific behavior under different body visualizations is rarely investigated. Therefore, the aim of the current study is to manipulate the presentation of the own body and to investigate the performance in virtual reality compared to reality in sports-related topics, such as balancing on a beam, as well as grasping and throwing a ball for young adults. We used the first-person viewpoint for all tasks. [38] showed that body ownership and embodiment can differ according to the viewpoint. The feeling of presence and embodiment are higher in first-person view [39] but third-person view can be more suitable for novices in motor learning [40]. Furthermore, first-person view is closer to reality than third-person view (side view).

For the development of a sports training scenario in VR, that will be accessible to every interested user, it is important to find out which parts of the body should be visualized in the training scenarios so that adequate training can take place. In addition, a high-developed VR scene was often associated with realistic and detailed properties, but not with it´s functionality in the context of VR training or movement execution [41]. For practical issues, the controllers of the VR-application were often used for visualization of the arms or fists. Having a motion capturing system, which enables the whole-body visualization in real-time is not conceivable for private uses. For sport-related task completion, it should be examined how much of the own body must be perceived. Therefore, the aim of the current study was to find out the meaning of the visualization of different body parts for the quality of movement execution and to derive future guidelines for virtual body presentation. Therefore, young and healthy participants complete three tasks in both conditions: balance task, grasping task, and throwing task. The tasks were chosen because they differ in the needed abilities to complete them and we did not want to specialize in just one. VR can be seen as a useful tool to study human behavior and to examine the impact of body visualization on sports performances since the visual system plays a decisive role during experiences in virtual environments [9]. With less visible properties of the own virtual body, we assume that decreased embodiment leads to significantly worse performances in sport motoric tasks. For this, we manipulated the presentation of the virtual body by occlusion of different body parts and partly manipulated objects and targets (a balance beam, a ball, and a ball cart). Based on previous literature highlighting the importance of the body presentation, we expect that the occlusions of the virtual body will lead to a decrease in performance. Besides, we also analyzed and compared human performance between reality and VR in order to detect possible differences between the conditions. Due to the creation of a very realistic virtual environment and the freedom of natural movements, we expect no differences in performance between reality and VR for the condition presenting the whole body.

## Methods

### Participants

20 healthy students (13 male, 7 female, age: 21.6 ± 1.6 years) with normal or corrected-to-normal vision participated on a voluntary basis. All participants were informed about the aim and procedures and gave their written consent. The approval of the Ethics Committee of the Otto-von-Guericke University at the Medical Faculty and University Hospital Magdeburg was obtained under the number 132/16. A self-made questionnaire assessed that the majority of the participants had a great interest and an open mindedness regarding new technology and VR during research. Therefore, a scale was used with 1 point (does not apply) to 5 points (does apply). The results showed great curiosity of the participants (scale: 4.8 ± 0.4). Besides, 81% of the participants stated pre-experiences regarding the participation of VR-studies.

### Motion capturing and visualization in VR

To realize the whole-body visualization in the VR, the participants wore a black motion suit on which 53 markers were attached, including 5 markers attached to the HMD for the head-tracking. During the data collection of this study, finger tracking was not yet available. The marker setup followed the instruction recommended by the supplier (Vicon, Shogun, Oxford, UK,). Meanwhile, the objects were modeled, tracked and visualized in the same VR scene. These objects included a balance beam, a ball, a green pad, a chair, a small football goal in a ball cart.

To visualize the real-time human movement and the tracked objects in VR, two desktop PCs (source-PC and target-PC) were used and they were connected directly via an internet cable to ensure the high stability and performance of data transmission. The source-PC (equipped with Intel i7 CPU, 32 GB memory, 512 GB SSD, and Nvidia Quadro K2200 4GB graphics card) was running the motion capture system (Vicon, England) with 13 infrared cameras at the sampling rate of 120 Hz. The software (Vicon Shogun, Vicon, England) for capturing the whole-body movement was used to stream the motion data to the target-PC. The target-PC (equipped with Intel i7 CPU, 16 GB memory, 512 GB SSD, and Nvidia GTX 1080 8GB graphics card) was running a self-modeled scene in Unity3D (version 2019.2.11f) and received the live data from the source-PC to drive the movement of the avatar in the VR. SteamVR Plugin for Unity (version 2.5.0) was used to enable all VR functions.

## Procedure

All participants first conducted three tasks in VR using a head-mounted display (HMD, HTC Pro Eye, with a total resolution of 2880 x 1600 Pixel, and a field of view of 110 degrees), and afterward, they repeated the tasks in real-world (RW). We chose this order because we assumed that it is easier to perform in RW compared to VR. Moreover, we wanted to provide a more comfortable procedure. In each condition, they started with the balance task, followed by the grasping task, ending with the throwing task. The three tasks are presented in Fig 1.

Four different body visualization conditions were applied in randomized order, and each condition was performed three times in a single task. Thus, 12 repetitions were performed in VR for each task and only three repetitions per task were conducted in RW since the body visualization condition could not be changed. Within every task, we obtained different parameters to assess the sports performance (which is described later). However, it is possible that no differences between the conditions (VR and RW) can occur especially between the different presentations of the virtual body at the expense of a greater cognitive load (e.g. participants need to concentrate more on the tasks). Therefore, immediately after completion of every single trial in every task, we also asked the participants how difficult they rate each trial and we noted these verbal reports. To measure the estimation of difficulty, we used a scale from 0 points (no subjective difficulty) to 10 points (very difficult). Independent of the performances, we were interested in the subjective estimated difficulty of all tasks, since being in an artificial world could lead to the impression of unfamiliarity or discomfort.

The procedure in VR is given in Fig 2. The total duration of the experiment per participant lasted 2 hours and the duration inside VR was around 30 to 40 minutes. Prior to the beginning of the tasks, the participants were free to move around in the virtual environment for 1 minute to get familiar with it. After the tasks in VR were done, the participants had one minute to adjust and recover their visual perception before starting the tasks in RW. This prevents a further time delay and an additional factor of harming participants' patience. After procedures in VR, the participants conducted the same tasks in RW. As well as in VR, they started with a 1-minute familiarization phase. For all tasks, three trials for each task including only one visualization, whole-body visualization (WB), were conducted by the participants.

**Balance task.** For the balance task, the participants were instructed to walk forward as fast and as accurately as possible over a balance beam laying on the ground with a width of 10 cm,

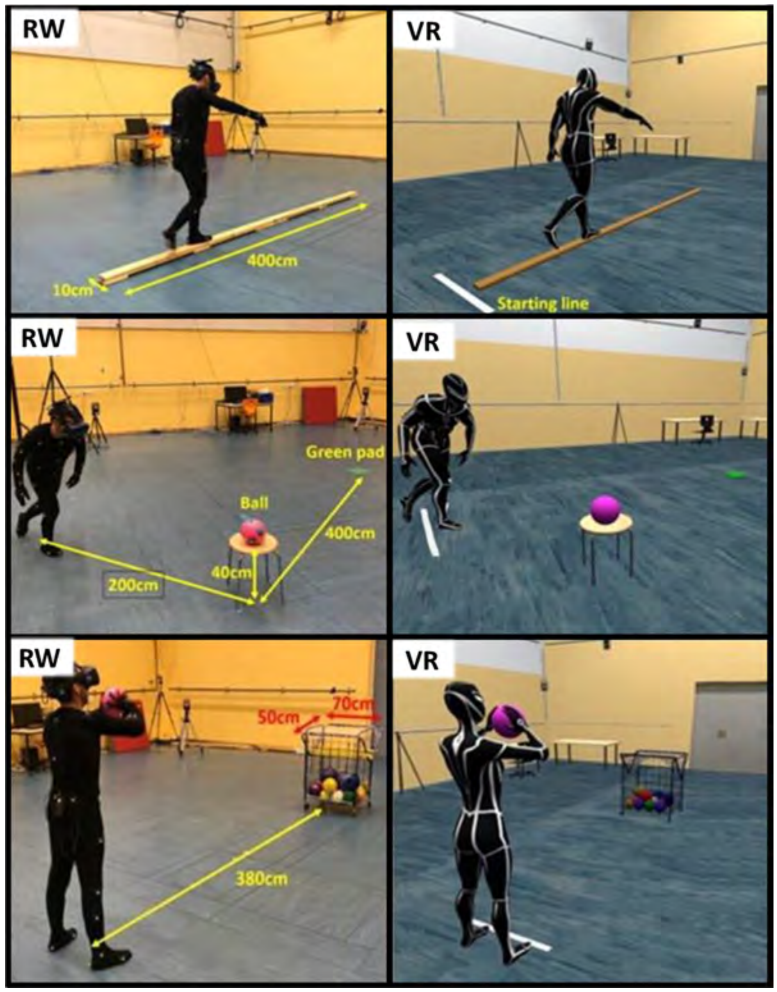


**Fig 1. Overview about the different motoric tasks.** Balance task (upper panel), grasping task (middle panel) and throwing task (bottom panel) in real-world (RW) and virtual reality (VR). The same order of magnitude was created in both conditions.

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a height of 4 cm and a length of 4m. The participants waited at the starting line in front of the beam (Fig 1), should then walk across it until the end and step down on the ground with one foot after the other. For familiarization in VR, the participants should perform ten trials with whole-body visualization. The parameters, which were obtained to analyze the performance, were the time for completion (time from a verbal "Go"-signal until both feet of the participants touched the ground at the end of the beam), the number of errors (reflects the number when the ground has been touched with one or both legs), and the number of foot strikes on the beam. The different body visualizations are presented in Fig 2.

**Grasping task.** The participants were instructed to start on a given start point (a virtual line on the floor), then go to a ball, grasp it, and put it carefully in a given target area (a green pad 30x30cm) on the floor. In this case, carefully means that the ball must not roll away from the target area. The total distance between the start point and the target area was always 6m. However, the location and the height of the ball changed (either the ball lay on the floor or a chair with a height of 50 cm. We chose these variations to ensure some variation and not to make the task too easy. Again, the completion of the task should be done as fast and as

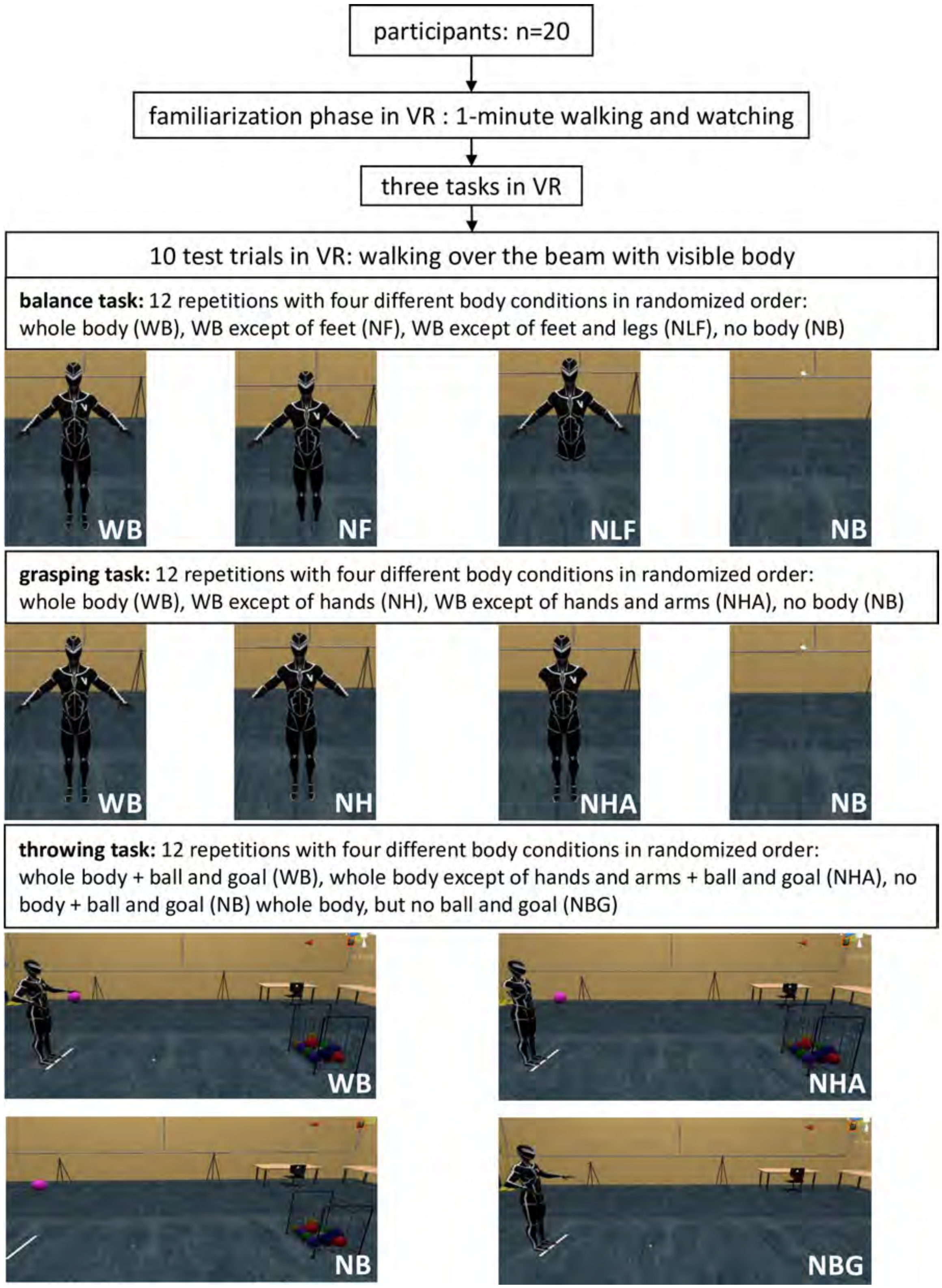


**Fig 2. Procedure of the study related to VR.** This figure shows the different body part visualizations. The visualization of the whole scene including all visualized objects is given in Fig 1.

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accurately as possible. As parameters served the time for completion (time from a verbal "Go"-signal until the ball hit the target area), and the quality using a scoring system (0 points: grasping and dropping the ball on the target area failed, 1 point: only grasping or dropping of the ball worked, 2: points: grasping and dropping of the ball was performed properly). The body visualizations in VR were whole body (WB), no hands (NH), no hands and arms (NHA), as well as no body (NB) (Fig 2).

**Throwing task.** The participants should throw a ball with both hands (like a chest throw in basketball) into a goal (50 x 70 cm) with a distance of 3.80 m and a height of approximately 1m. According to a scoring system, we analyzed, if and how the ball landed in the goal or not (0 points: ball did not touch the goal, 1 point: ball touched the bars but not the net, 2 points: ball touched the net, see Fig 1). The net was not visualized in VR. As body visualizations, we provided the whole-body (WB), no hands and arms (NHA), as well as no-body (NB) (Fig 2).

## Data analysis

45 trials (36 trials in VR with 12 per task, and 9 trials in RW with three per task) recorded for each participant, thus 900 datasets were obtained with no dropout. All tasks were filmed using a camera (GoPro Hero 6, 60 Hz). The videos were analyzed with the Windows Media Player (Microsoft, Redmond, USA, version 12.0.18362.418) and Magix Video Deluxe Premium (Magix software GmbH Berlin, Germany) to determine the different parameter.

For each performance parameter (time for completion, number of errors, number of the foot strikes in the balance task, and quality in the grasping task and throwing tasks), as well as for the subjective difficulty, Friedman tests were applied with body visualization as a within-subject variable. When the data featured the requirements (no outliers, normal distribution, and sphericity), one-factor variance analysis with repeated measurement ANOVA was conducted. For each task and parameter, we compared four different body visualizations (every four conditions in VR). Furthermore, Dunn-Bonferroni-post-hoc-tests with an estimation of effect sizes were carried out. Effect sizes were obtained using Pearsons' correlation coefficient (r) being defined as $r = 0.1$ small effect, $r = 0.3$ moderate effect, and $r = 0.5$ large effect. The level of significance was set to $\alpha = 0.05$. All analyses were carried out with SPSS, version 25. Depending on the data type, we used either t-Tests for dependent samples or Wilcoxon tests to reveal possible differences between RW and VR (WB). In some cases, the number of participants is reduced due to the appearance of significant outliers, which were detected using box-plots graphs.

# Results

Concerning the aims of the study, the results were divided into two parts. The first step was to focus on the comparison of the participants' accomplishments between the two conditions RW and VR. The results of each parameter and each task are provided in Table 1. For the comparison between the conditions, we considered the whole-body visualization (WB) in condition VR. The main part of the results constitutes the influence of the different types of body visualization in VR, which is shown in Table 2.

Most significant differences occurred between RW and VR(WB) but not within the different VR conditions. The participants performed significantly better in reality compared to VR (WB). In reality, they had shorter times for completion, fewer foot strikes on the beam, and the subjective estimation of difficulty were perceived lower in reality compared to VR(WB). However, no significant differences were detected between RW and VR(WB) in the number of errors during balancing as well as in the quality of throwing and grasping.

**Table 1. Results of the comparison between real-world (RW) and virtual reality (VR/WB) for the three tasks.**

| Parameter | RW | VR / WB | two-tailed | | effect sizes (Pearson's r) |
|---|---|---|---|---|---|
| | | | Z | p | |
| **Balance task** | | | | | |
| time for completion (s) (n = 19) | 4.21 ± 0.95 | 5.93 ± 1.57 | -3.783 | .000 | r = 0.60, large effect |
| number of foot strikes on the beam (n = 20) | 8.52 ± 1.27 | 10.03 ± 1.37 | 6.630 | .000 | r = 0.83, large effect |
| number of errors (n = 18) | 0.07 ± 0.24 | 0.24 ± 0.42 | -1.549 | .121 | - |
| subjective estimation of difficulty (1: easy -10: very difficult) (n = 20) | 2.15 ± 1.14 | 3.58 ± 1.43 | -3.397 | .001 | r = 0.54, large effect |
| **Grasping task** | | | | | |
| time for completion (s) (n = 19) | 2.98 ± 0.27 | 3.78 ± 0.36 | 11.964 | .000 | r = 0.94, large effect |
| quality due to score system (0: bad-2: very good) (n = 20) | 1.82 ± 0.28 | 1.70 ± 0.21 | -1.507 | .132 | - |
| subjective estimation of difficulty (1: easy -10: very difficult) (n = 20) | 1.48 ± 0.70 | 2.65 ± 1.35 | -3.556 | .000 | r = 0.56, large effect |
| **Throwing task** | | | | | |
| quality due to score system (0: bad-2: very good) (n = 20) | 1.75 ± 0.36 | 1.68 ± 0.55 | -.241 | .81 | - |
| subjective estimation of difficulty (1: easy -10: very difficult) (n = 20) | 2.03 ± 1.01 | 2.98 ± 1.37 | -3.089 | .002 | r = 0.48, moderate effect |

Mean ± SD are given for each condition. Significant differences between each condition within each parameter are provided using Wilcoxon tests or t-Tests. The estimation of effect sizes (Pearson's correlation coefficient r) is given. Only the whole-body visualization (WB) in VR was used for the comparison to RW-performances. The number of participants is given by n.

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We found significant differences between the different types of body visualization, which had a large effect for the parameters "time for completion" and "number of foot strikes on the beam" in the balance task, as well as small effects in the "quality of throwing due to score system" and "subjective estimation of difficulty" in the throwing task. The differences within the VR body visualization consist mainly through no-body visualization (NB) compared to the others (see Table 2). Of course, a moderate effect on the quality of throwing and subjective estimation of difficulty is observable when the goal and ball (NBG) were hidden in the participant's view (see Table 2).

The following graphs give an overview of the performances of the participants within each body visualization type.

## Discussion

Due to the ever-increasing computing power and the representations of realistic-looking virtual scenes, we first examined whether the behavior (in this case the performances of participants) was comparable to that from RW. We found significant differences between VR compared to reality in all three tasks: balancing, grasping a ball from different height and laying it on a target in different distances, and throwing a ball into a target (ball cart) with a chest pass. Performance in reality was better compared to VR. Especially, the time factor differs with large effects between both conditions. The participants stated of having an uncomfortable feeling to complete the balance task and recognized more instability in their performances. The participants were not used to seeing their environment through computer graphics, which could be an explanation for insecurity. However, the goal of each task was achieved with no significant differences in the number of errors (balance task), grasping, and throwing with no significant differences in quality. The subjective estimation of difficulty was higher in VR compared to RW in all three tasks, and the way to reach the goal (significant difference in the number of foot strikes on the beam and time for completion in the balance task) was partly different. Concerning the number of errors, the result is in line with previous work, which found that similar sports performance could be attained in reality and VR (for handball see

**Table 2. Results of the three tasks.**

| **Balance task** | | | | | | |
|---|---|---|---|---|---|---|
| **Parameter** | **WB** | **NF** | **NLF** | **NB** | **Significance between the body conditions using Friedman tests/ ANOVA** | **Dunn-Bonferroni-post-hoc-tests and effect sizes (Pearson's r) for significant differences** |
| time for completion (s) (n = 19) | 5.93 ± 1.57 | 5.80 ± 1.05 | 5.79 ± 1.41 | 6.82 ± 1.86 | $\chi^2$ (3) = 19.863, p<0.001 | NF-NB: p<0.001, r = 0.84 (large effect) |
| | | | | | | NLF-NB: p<0.001, r = 0.89 (large effect) |
| | | | | | | WB-NB: p<0.001, r = 0.75 (large effect) |
| number of foot strikes on the beam (n = 20) | 10.03 ± 1.37 | 10.03 ± 1.33 | 10.10 ± 1.60 | 10.98 ± 2.10 | $\chi^2$ (3) = 21.313, p<0.001 | NF-NB: p<0.001, r = 0.82 (large effect) |
| | | | | | | NLF-NB: p<0.001, r = 0.80 (large effect) |
| | | | | | | WB-NB: p<0.001, r = 0.81 (large effect) |
| number of errors (n = 18) | 0.24 ± 0.42 | 0.20 ± 0.26 | 0.09 ± 0.15 | 0.28 ± 0.47 | $\chi^2$ (3) = 2.767, p = 0.429 | - |
| subjective estimation of difficulty (1: easy -10: very difficult) (n = 20) | 3.58 ± 1.43 | 3.65 ± 1.82 | 3.48 ± 1.80 | 3.98 ± 1.98 | *F* (3, 57) = 1.607, p = 0.198 | - |
| **Grasping task** | | | | | | |
| **Parameter** | **WB** | **NH** | **NHA** | **NB** | **Significance between the body conditions using Friedman tests** | **Dunn-Bonferroni-post-hoc-tests and effect sizes (Pearson's r) for significant differences** |
| time for completion (s) (n = 19) | 3.78 ± 0.36 | 3.80 ± 0.54 | 3.79 ± 0.45 | 3.65 ± 0.50 | *F* (3, 54) = 1.528, p = 0.218 | - |
| quality due to score system (0: bad-2: very good) (n = 20) | 1.70 ± 0.21 | 1.77 ± 0.22 | 1.73 ± 0.28 | 1.87 ± 0.17 | $\chi^2$ (3) = 6.959, p = 0.073 | - |
| subjective estimation of difficulty (1: easy -10: very difficult) (n = 20) | 2.65 ± 1.35 | 3.03 ± 1.73 | 3.17 ± 1.85 | 3.15 ± 2.10 | $\chi^2$ (3) = 4.842, p = 0.184 | - |
| **Throwing task** | | | | | | |
| **Parameter** | **WB** | **NHA** | **NB** | | **Significance between the body conditions using Friedman tests** | **Dunn-Bonferroni-post-hoc-tests and effect sizes (Pearson's r) for significant differences** |
| quality due to score system (0: bad-2: very good) (n = 17) | 1.68 ± 0.55 | 1.42 ± 0.52 | 1.32 ± 0.59 | | $\chi^2$ (3) = 13.176, p<0.05 | WB-NHA: p<0.05, r = 0.24 (small effect) |
| | | | | | | WB-NB: p<0.05, r = 0.34 (moderate effect) |
| subjective estimation of difficulty (1: easy -10: very difficult) (n = 20) | 2.98 ± 1.37 | 3.55 ± 1.67 | 3.47 ± 1.81 | | $\chi^2$ (3) = 37.153, p<0.001 | WB-NB: p<0.05, r = 0.20 (small effect) |
| | | | | | | WB-NHA: p<0.05, r = 0.29 (small effect) |

Mean ± SD are given for each body visualization condition. Significant differences between each condition within each parameter are provided using Friedman tests or ANOVA. Significant post-hoc-tests and estimation of effect sizes (Pearson's correlation coefficient r) are given. Body visualization conditions: WB: whole body condition, NF: no feet, NH: no hands, NLF: no feet and no leg, NHA: no hand and arms, NB: no body. The number of participants is given by n.

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[42] and for karate see [35]). However, similar performance can be reached on the expanse of different motor execution [42], which can also be dependent on the level of graphical detail [43].

Several studies in VR exist, which analyzed static balance (e.g. [44]), or dynamic balance using force plates (e.g. [45]). In therapy, and especially with older adults, it was found that VR balance interventions had more benefits than conventional balance training (e.g. [46]). However, such studies compared reality and exergames (Desktop VR) [47], and not immersive HMD based VR. In the current study, we examined dynamic balance when comparing balancing over a balance beam in VR with reality. The performance was worse in VR compared to reality because significantly more time was needed and more foot strikes were taken to complete the task. However, It should be emphasized that on average, the difference in the numbers of foot strikes between RW and VR was quite low, and therefore, a small amount of time delay occurred (see Table 1). Although the properties in the current virtual scene were identical to those from the real environment, the development of higher sophisticated realistic-looking virtual scenes through increased computing power could reduce those minimal differences. Nevertheless, the participants' subjective impression of the virtual room was good. This was confirmed through their given feedback, in which 75% of the participants perceived the virtual room as realistic or quite similar to the real environment. Just 5% of the participants were focused on the fun factor, and the remaining percent stated unfamiliarity and blurriness.

Many ball sports in VR examined interception of balls, such as anticipating landing points and analyzing the influence of ball spins. However, only a few studies investigated throwing in VR so far (for review see [37]). [40] found that learning free throws in a CAVE is best when beginners see their performance from third-person perspective and with additional ball flight information (ball trajectories). However, that scenario is not realistic with learning in reality, therefore, we decided to perform each task with first-person perspective. [48] analyzed throwing with different distances and found that with increasing distance to the target, the performance decreases. Therefore, we chose a quite close distance. Compared to WB condition, the different types of visualization, the NHA, and NB differ in the quality as well as in the subjective estimation of difficulty. That difference showed that for throwing quality, it is easier when the whole body is visible all the time. The occlusion of the body parts probably harmed memorizing the target position and its' properties.

The main goal was to analyze the importance of virtual body presentation in VR on participants' performances. For each task, we chose specific parameter regarding the quality of performances. We defined a loss in the performance quality if the number of errors and the time for completion increased. In the balance task, we valued a high number of taken foot strikes as a factor of insecurity, and therefore as a further negative impact on performances. Which strategy was chosen to step over the beam is often influenced by the given instructions. Since the instructions were the same, we assumed to see a difference in the behavior or performances of the participants caused by the conditions. To minimize the effect of being in an unfamiliar environment, we included 10 test trials in VR. We were also interested in the subjective estimates of difficulty as well since the impression of the participants could be influenced by not have the feeling of being present, or not feeling of being embodied. In the balance task, the NB condition was observed as the worst compared to the other visualization types (see Fig 3). It could not be shown that an increasing reduction in the visibility of the limbs also leads to an increasing deterioration of the performances. Regarding the number of errors or the time for completion, the performances seemed to improve after removing the feet and legs from vision. Perhaps, for balancing, it is not necessary to fixate the feet or the legs to complete the task. This could also be seen in the throwing task, in which the WB visualization led to the best results through the predefined parameter. This is observable through the reached points in the scoring system. However, in the grasping task seems to be no influence due to the different body visualization types (see Fig 4). Here, the participants' performances were best in the NB condition regarding the values of the scoring system and the shortest duration of movement execution. In this case, the results suggested that the visualization of the body limbs in VR could be more distractive and led to decreased performances. However, some participants stated that the different types of visualization were often not noticeable due to the limited field of view (FOV) of the HMD in the grasping and throwing task, whereas the visualization of the feet and legs were crucial within the balance task. This could be an explanation for the small number of effects

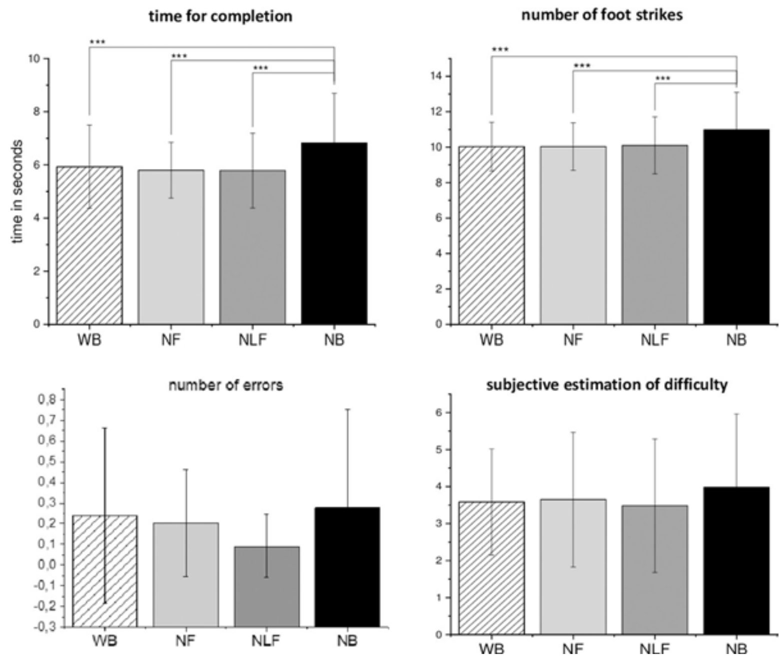


**Fig 3. Overview of every parameter for the balance task.** Black bar indicates the value for whole-body (WB), the grey bar for no leg and feet, the blue bar for no feet and the red bar for the no-body visualization. The probability of error is indicated through * = p≤0.05; ** = p≤0.01; *** p≤0.001.

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between the different visualization types and is also discussed in limitations and future directions.

Regarding the embodiment, we ensured an enhanced sense of self-location through the first-person-perspective and because of including associated tactile information when the participants have reached out to the ball. Here, the properties of the presented avatar (provided by Vicon) did not fit perfectly for each participant. Although we used a female avatar for a female participant and vice versa, the individual properties of every single body were not reached. When the participant grasped the ball, the fingers were not perfectly hit the surface which could lead to less embodied feeling. The visual-tactile correlations were less compared to the real-world condition. Therefore, a minimal loss of the sense of self-location in the VR must be considered. The sense of agency was provided since the full-body movements of the participants were tracked by using reflective markers, which were attached to the participant´s limbs [12]. Unfortunately, we could not control possible latencies that can occur due to the use of wireless adapted for the HTC Vive Pro. The participants did not recognize any latencies or disruptions of presenting the virtual scene. For the sense of body ownership, the avatars' appearance was human-like, but, as mentioned before, the morphological similarity between one's biological body and the virtual one was not provided perfectly. Therefore, the sense of body ownership could have suffered, due to reduced top-down processes, which have a positive aftermath on the perception of ownership of the virtual body. We conclude that the presentation of a realistic whole body without delays and offset is helpful for performance analyses in VR, even for young and healthy participants and with quite easy tasks. Otherwise, the participants need time to get used to it and adjust their performances, which is not reflecting real-world conditions. The main result that has been emerged from the data is that whole-body visualization leads to better results in each tested motoric task than no-body visualization. Overall, the different types of body visualizations seemed to have no significant impact on the

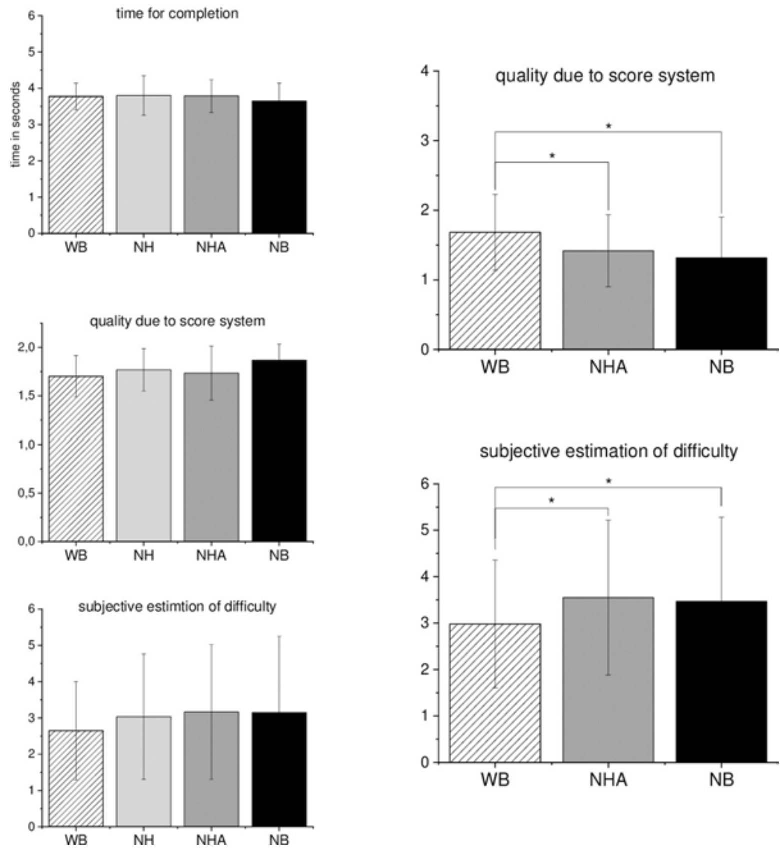


**Fig 4. Overview of every parameter for the grasping and throwing task.** Black bar indicates the value for whole-body (WB), the grey bar for no leg and feet, the blue bar for no feet and the red bar for the no-body visualization. The probability of error is indicated through * = $p \leq 0.05$; ** = $p \leq 0.01$; *** $p \leq 0.001$.

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participants' performances. Perhaps, most participants were focused on a specific fixating point in the background during balancing. Therefore, a reduced view of body segments would have no negative influence. Although the application of more technology (in this case the tracking technology for real-time motion capturing of the whole body) often leads to greater problems and higher delays, we had no technical problems. The application of Vicon Shogun and the motion suits (Fig 1) were described as very user-friendly by the participants.

## Limitations und future directions

We need to mention some limitations of the current study. The used HMD had a limited field of view (110˚) compared to the eyes in reality (approximately 180˚) but this is the case with almost all HMDs. However, that limitation in vision could have led to worse performance in VR compared to reality. The participants often complained that the different visualizations were not noticed at all due to the limited FOV in VR. A larger FOV would solve the problem so that a more realistic impression of the scene could be obtained. In addition, during the balance task, some participants focused on a visual point at the end of the beam. Therefore, they did not even recognize that the feet or legs were not visualized. Additionally, an integrated eye-tracking system could be included to measure participants' gaze behavior during their performances, since not all participants focused on their limbs during task completion. Furthermore, immersion as a quantifiable aspect of the simulation and the subjective feeling of presence, as well as natural behavior in VR contextual, psychological, personality, and emotional aspects are also very important [13]. However, we did not include further questionnaires to assess further aspects, such as presence or cybersickness. Our participants told us later that they had no problems with cybersickness (at exposure time to VR of around 30 minutes) and they rated the VR and the virtual body to be realistic.

An additional factor that limits the current study is the measure of the presence or the experiences of body ownership [49]. The focus was to analyze the performances during the different motoric tasks and to compare them between the conditions. Established questionnaires could have been used to amplify the knowledge about the impact of different body visualization types. Also, it is recommended to measure physiological responses and behaviors, which may indicate whether the participants felt that they were in the scenario [12]. The results suggest that an impact on the feeling of presence just occurred when no-body visualization was used since the quality of participants' performances decreased.

Although we randomized the body presentations in all tasks, the "no-body conditions" occurred in the first half of the 12 repetitions. Thus, the order could have affected our results. Moreover, when occluding the whole body, which is a very unfamiliar situation, participants need to rely more on body information (proprioception and muscle sensations). On the one hand, that situation can be used for training to trust more on own body information, but on the other hand, maybe the familiarization phase (one minute watching the VR scene and ten times walking over the beam in whole-body condition in VR) were too short.

We did not analyze the performance with different types of virtual bodies in VR. We only provided a virtual body (with male and female properties) of the same height as the tested person but the shape was similar for each participant. Both in reality and in VR, the participants wore a black motion suit with the attached markers, and in VR, they saw a black-dressed avatar (Fig 1). In future studies, it should be analyzed if the performance changes when the avatar (as the own body) is even modeled closer to the own real body related to the visual-tactile, visual-proprioceptive and visual-motoric matching.

We are not able to derive further recommendations for different tested groups or athletes of different ages, gender, and sports. We could show that the methods used in the current study are appropriate to analyze performance and behavior in VR and reality. The sports-related tasks are doable for young and healthy adults. Although they seem to be quite easy in reality, we found significant differences between VR and reality. However, the subjective estimation was only low and moderate for the tasks in both conditions. Therefore, it would be interesting to repeat our study with different participant groups (e.g. different ages, different sports backgrounds, or athletes of different expertise levels) and to further include more tasks, which could also be more sports specific.

Another interesting aspect would be the transfer from VR to RW. If the quality of the movements, which were only learned or performed in VR, can be transferred to the real environment, it can be assumed that the perception from VR is the same as in the real one.

## Conclusion

The current study is the first study comparing sports-related tasks in VR and in reality with further manipulations (occlusions of body parts) of the virtual body visualization. Realistic virtual environments and objects were provided and natural movements were allowed. Due to the lack of haptic feedback in VR, we gave the participants a real ball for grasping and throwing and a real balance beam, which were virtualized in real-time. Thus, realistic conditions were ensured. However, significant differences in the performance in all tasks were found between reality and VR, especially in the time of completion and the subjective estimation of difficulty.

Moreover, the results show that the whole-body visualization leads to the best performances (lower time of completion, number of foot strikes during the balance task) in contrast to the other visualization types, especially for the no-body condition. We conclude that the visualization of a realistic virtual body is helpful to limit differences between both conditions and to ensure quite natural body perception. For task completion, however, it is not always necessary to visualize the whole-body, since no differences in performances could be detected for the reduced vision of body limbs. For studies analyzing perception and sports performance or for VR sports interventions, we recommend at least the visualization of the task-specific body parts, such as during throwing the hands and arms or during balancing the feet and legs in real-time. Besides, a further experiment may provide information on whether the participants used the incoming visual information in VR to complete the balance task. We observed habituation on performances, especially during the balance task. Therefore, we concluded to let the participants walk blindfolded over the beam to exclude visual information. Probably it is still possible to succeed due to haptic feedback, which would lead to similar quality in performances compared to VR conditions.

## Author Contributions

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**Supervision:** Stefan Pastel, Katharina Petri, Kerstin Witte.

**Validation:** Chien-Hsi Chen, Katharina Petri.

**Visualization:** Stefan Pastel, Chien-Hsi Chen, Katharina Petri, Kerstin Witte.

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**Writing – review & editing:** Kerstin Witte.

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