Virtual Reality Simulators for Inclusion and Participation: Broadening Perspectives on Accessible Cities and Public Space

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1 ABSTRACT

The design of urban public space often involves a convergence of different actors with different priorities in the use of available space. This becomes evident when different modes of transport are combined in the very limited space available. At the same time, the growing and aging population strengthens demands for action in public space design towards better accessibility and involvement of the vulnerable. Innovations in digital design and simulation tools have shown a great demand to address these challenges as they have the potential to facilitate mediation and improve citizen science, participative and collaborative planning processes. Joint evaluation is supported and planners, decision makers and foremost citizens are brought together [(Yang et al. 2019), (Sanchez-Sepulveda et al. 2019), (Buffel et al. 2012)]. In our research, we have implemented human-computer interfaces for urban digital twins. These digital twins combine geometry and point cloud models, simulation results, and sensor data and enable analysis of existing situations, scenario testing, as well as prediction, on all urban scales, from buildings to cities and regions. By visualization in VR environments such as a CAVE (Cave Automatic Virtual Environment) they provide a powerful method for informed discussions between all stakeholders which is essential for joint decision-making. Our recent work extends these tools to include often neglected groups, such as people with disabilities, the elderly, or children, with the aim to empower them and to address their specific needs with respect to public spaces, while making these needs more traceable for others. Therefore, we have implemented different modes of traffic in simulators: Cars, bicycles, skateboards, and wheelchairs. Using one of these simulators, users can then interactively explore virtual replicas of public spaces using a real vehicle for steering. In combination with a tracking system, the user’s perspective in the virtual world is adjusted accordingly, enabling an impression of riding through the replica similar as in a real environment. Users can explore the accessibility of public spaces and detect shortcomings like high curbs or slopes. Often, these are unnoticed by pedestrians while posing major obstacles for people in wheelchairs, with strollers or roller walkers. Hence, this simulator helps to better understand and include the mentioned group in public participation. Moreover, the simulator was combined with traffic simulations (Zeile et al. 2021). These, in particular when visualized along with the digital twin, improve the depiction of the actual processes and dynamic scenarios, and allow to simulate and compare scenarios of different design proposals. Bottlenecks such as narrow sidewalks incapable of handling the load of pedestrians, or unclear intersections with an insufficient view can be detected as well as the use of space in certain conditions as during rush hours or at construction sites. Experiments were carried out using the different simulators as human-computer interfaces. Observations and questionnaires were used to analyse the experiences of 23 test subjects. In summary, the developed simulators are intended to contribute to safer and better accessible urban spaces for all. In this initial work, the focus lies on groups with special needs in public spaces - for example, highly mobile young people and in contrast people with limited mobility or the elderly. By detecting current barriers, the developed simulators make them tangible and understandable for the wider public but also for planners, designers, and decision-makers.

Keywords: Inclusion, Digital Twins, Public Space, Virtual Reality, Mobility

2 MOTIVATION

Public urban space is claimed by various actors, often with very different interests on how the limited available space shall be used. Urbanization and aging population amplify this problem as they pose even bigger challenges for future public spaces (UN Habitat 2021a). Marginalized groups of actors are often neglected in the design of public space. However, especially when associated with special needs, as people with disabilities or the elderly, their demands are essential to be able to participate in public life at all. The COVID-19 pandemic has even aggravated their vulnerability (UN Habitat 2021b).

Thus, there is need for an approach to unify the different needs through solutions which support all actors. This, however, requires mutual understanding of the respective other interests. Therefore, a tool is required which allows to depict these demands and make them traceable for other actors. At the same time, this tool should add value not only for citizens but also planners and decision makers to ensure consistency of information. A uniform communication tool which allows for tangible experience of urban space in various perspectives and integrates visualization and interaction could solve these challenges.

Furthermore, it could help to generally include a broader range of citizen and provide low-barrier access to more diverse and complex data. Moreover, experiences taught that inclusion of citizen and visualization of the project helps to increase acceptance in planning processes (Münster et al. 2017).

3 STATE OF THE ART

The inclusion of often neglected groups has been investigated in several works during recent years. (Buffel et al. 2012) explored the situation of the elderly in urban environments by determining changes and restrictions in cities. The focus of their work lies on assessing the current level of age-friendliness of cities and how to involve older people in development processes. (Yung et al. 2016) identified the needs of the elderly regarding public space, whether they are addressed and how they differ from planned and realized considerations. (Shahraki 2021) research considers urban planning for (physically) disabled people. They combined theoretical studies, case studies and weighted sum methods to derive planning procedures to specifically include disabled people. Inclusion of all was the subject of research by (Rebernik et al. 2019) who developed a 4-dimensional theoretical model. Their combined methodological approach showed benefits in understanding the complexity of cities and addressing needs of people with different impairments. Research showed that many contributions in this field consider the assessment rather than approaches for solutions or propose theoretical methods. This braces the need for tools that go beyond assessment and support the development of practical solutions. Digital tools are on the rise for tackling the challenges associated with inclusion in urban spaces. (Hasler et al. 2017) researched the value of digital tools for citizen participation in urban planning by developing a conceptual framework to classify their potential. Their work concludes by stating that digital tools are a valuable extension of current methods. (Szarek-Iwaniuk et al. 2020) conducted a case study in smart cities where e-Participation is used for co-creation of urban space. Further, they discussed the value of ICT technologies for participation and presented a Public Participation GIS. (Zeile et al. 2021) compared methods of real and virtual spaces for detecting conflicts in traffic systems to design optimization strategies for road courses. Their work combines the assessment of existing situations with simulations of scenarios. Smart cities, as an application of digital tools, were explored by (de Oliveira Neto 2018) to leverage their potential in favor of disabled people. They initiated the concept of Inclusive Smart Cities by employing a multi-instrument approach to determine the needs of different stakeholders. Based on the latter, the authors suggested tools for practitioners and a conceptual model using inclusive smart objects to assist people with disabilities in the exploration of urban spaces. (Dembski et al. 2020) presented urban digital twins on a case study of a small town in Germany. They combined various models and data into an all-encompassing model, establishing links between the different disciplines and levels, and visualization of the digital twin in Virtual Reality (VR). Comprehensive visualization techniques such as 3D or VR were presented to improve participation processes and engagement and lower barriers as evidenced by (Dembski et al. 2019) or (van Leeuwen et al. 2018). (van Leeuwen et al. 2018) assessed the use of VR in public participation. 3D-rendered scenarios for redesign of a park were presented to citizen and experts for collective decision-making processes. The results showed a raise of engagement when using immersive technologies. VR is also employed in a study by (Sanchez-Sepulveda et al. 2019) in collaborative urban design through human-centric problem-solving. It demonstrates the use of digital tools in decision-making processes and social development as they raise satisfaction and improve public motivation. A concept involving Mixed Reality (MR) is used by (Wolf et al. 2020) who concluded that MR supports resolving the paradox of participation, which states that participation is typically higher the more advanced a planning process is, by providing clarity and reducing abstraction for participation. With respect to traffic, VR is used for scenario testing, training et cetera as described in works by (Ju et al. 2022) who used VR to investigate situational awareness in car accidents or (Lv et al. 2022) using VR-based simulations for intelligent vehicles.

4 IMPLEMENTATION

In this work, a simulator was developed which enables navigation in virtual worlds, in particular digital twins of urban spaces, through real vehicles. In the first approach, a skateboard was used and modified by two students by adding sensors and other hardware. The refactored skateboard was then embedded into a Virtual Environment to enable navigation within the digital twin using the real vehicle. In a similar approach, a bicycle and a wheelchair simulator were subsequently developed on the basis of real devices.

4.1 Visualization & Digital Twins

The Vistle visualization software (www.vistle.io) was used to create a 3D virtual world, or digital twin, in which users can navigate. Vistle is a visualization software for highly parallel distributed and interactive visualization in immersive environments. It integrates a VR renderer ('COVER') that provides further interfaces for various data formats to integrate simulation data, GIS, or BIM, among others. A new interface has been implemented to connect the vehicles to the visualization software. This allows new simulators to be recognized automatically as soon as they log on to the network. Besides, also traffic simulations were integrated into the digital twin, to establish close-to-reality traffic conditions. The simulations were created using SUMO (www.eclipse.org/sumo/).

The software was used on a dedicated cluster to power a CAVE (Cave Automatic Virtual Environment), a virtual reality environment with 5-sided back projection for multiple users. The vehicles were placed into the CAVE. Users were equipped with tracked 3D glasses for immersive 3D experience of the virtual world when riding the vehicles. The simulators can be used in different digital twins of cities.

4.2 Virtual Skateboard

The skateboard is based on an ESP32 microcontroller with an accumulator for power supply. The module sends its measured values via network or wireless LAN to the VR software (COVER). Weight forces are transmitted to the individual four wheels, which have been replaced by sensors for pressure and traction. Based on the data transmitted in this way, the software computes the driving dynamics: Lateral dynamics are computed from the current forces on the wheels to implement steering to the left or right. However, the implementation of realistic longitudinal dynamics (acceleration and deceleration) posed a greater challenge. Deceleration is only performed for topographical reasons such as driving uphill. This emulates the downward forces that act when riding a slope with positive incline. Acceleration is more complex: In an earlier stage of development, it was only possible to control the skateboard by leaning forward to accelerate or backward to brake. However, this process did not reflect the real movement well. After technical extension, acceleration is now also achieved via downhill propulsion. Once the user is rolling, the acceleration is dictated by the terrain. Acceleration can also be achieved by leaning forward when the speed falls below a certain limit. This corresponds to a bump or acceleration. If the user wants to slow down, the skateboard must be ridden uphill. When dismounting from the skateboard and no weight is applied, the skateboard automatically brakes.

4.3 Virtual Bike

The bicycle simulator is based on a real bicycle mounted to a Tacx© roller trainer. Connection to the VR software is established via USB. The software reports the current gradient to the trainer in order to increase the braking force and thus contribute to a more realistic riding experience. Unfortunately, positive feedback cannot yet be given when going downhill, as this is not supported by the hardware. As the speed is computed by the frequency of the bike's real wheel, deceleration is imposed by operating the brakes of the bike which natively slows down the rear wheel. The steering angle is read out via the existing USB interface of the trainer and transferred to the VR software. A disadvantage of this setup is that the inertia of the rider's body mass is not taken into account, as only the inertia of the rear wheel is measured while the bike is mounted to a framework on the wheel fork. Another disadvantage of the roller trainer is the large wear of the rear tire and consequently the "slippage" of the tire during acceleration. This can be perceived as very unpleasant and can be a trigger for cyber-sickness (Rebenitsch et al. 2016).

4.4 Virtual Wheelchair

As a third simulator, a commercially available modern wheelchair was converted. In a first phase, an undercarriage with four castors was developed. The main wheels were placed on the latter (two castors per wheel) while the smaller front wheels rested on a metal console and had no direct function in the simulator.

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In this way, it is possible to turn the two main wheels separately for navigation and locomotion. The castors, which are designed as encoders and recorded the movements, were controlled by an ESP32 which transmits the current position of the wheels to the VR environment.

In order to make the experience more realistic, the castors have since been equipped with servo drives. This allows forces to be actively transmitted to the hand wheels with smooth tires, enabling realistic deceleration and acceleration for the user. This design is also sufficient to allow the wheels to slip and corresponds to a real wheelchair on a smooth road. The new control operates via a Raspberry Pi 4 single-board computer running real-time Linux and a real-time Ethernet network for control tasks. In this way, the current actual values can be read out and torques can be specified. The actual values are transmitted back to the software via the network.

5 EXPERIMENTS

The virtual vehicles or simulators were used by subjects in various test scenarios. Initially, users were asked to freely move in the virtual world to familiarize with the simulators (‘training phase’). Subsequently, they were asked to solve different tasks as described below (‘performance phase’). Finally, their feedback was obtained by means of a questionnaire (‘evaluation phase’).

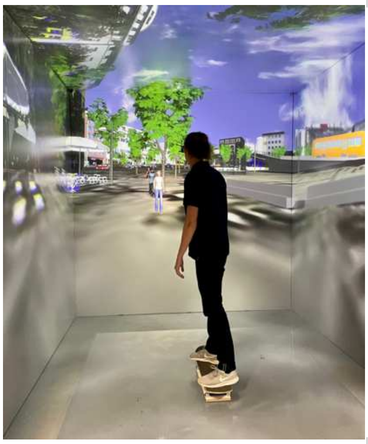
5.1 Setup

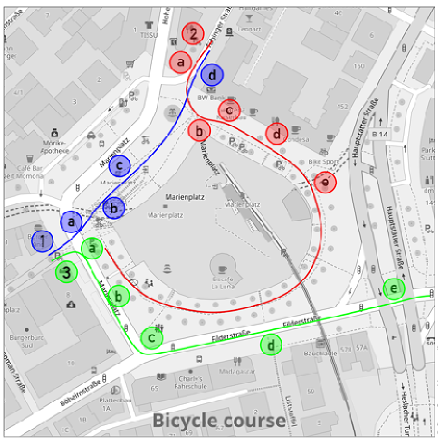
Each test person was assigned to one of the two vehicles (bicycle, skateboard). They could then use the vehicle to navigate through the visualization of the digital twin. The virtual setting chosen was Marienplatz in Stuttgart, a typically busy square where different modes of transport meet and also come into conflict with each other. The test persons were asked to navigate to a specific location.

The VR model included traffic simulation for cars, pedestrians, bikes, and other vehicles to improve the reference to the real urban space. This exposed the subjects to various situations that allowed to capture conflict situations between road users, accessibility of spaces and reaction to unexpected changes. The scenes were chosen depending on the vehicle used, as different conditions also prevail in real space.

For the subjects riding the bicycle three tasks were presented (Figure 2). Task 1 consists of a mostly straight stretch of different types of infrastructure. It starts on and follows the city's main cycling route for about 130m which can be considered quite challenging. It leaves a narrow alley and confronts the subject with crossing a light shared with pedestrians (a), entering a zone with pedestrians with very unorganized paths (b), through a small gap between a subway escalator and a bus stop (c) and merge with motorized traffic at the end (d).

Task 2 introduces more turns and speed variation to the subjects. They have to cross motorized traffic at a left turn (a), avoid an obstacle which is a set of stairs (b), encounter more pedestrians (c), moving through the outdoor catering of restaurants and cafes (d) and entering a long right turn which allows higher speeds.





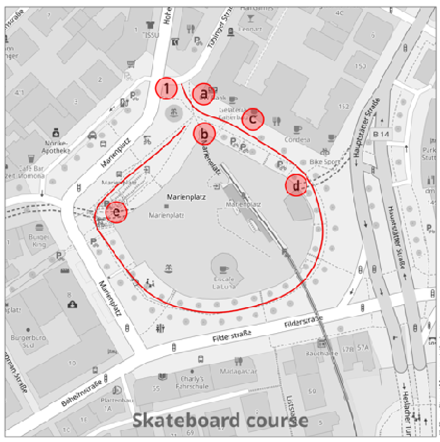


Figure 1 (left): Test person using the skateboard simulator in a CAVE. Figure 2 (center): Bicycle courses. Figure 3 (right): Skateboard courses

In task 3, more interaction with motorized traffic is presented to the subjects. They were asked to do a right turn and merge with traffic (a), approach a traffic light and choose wether to wait or to pass slow moving traffic (b), perform a left turn at the light (c), enter multilane-traffic (d) and finally to cross another very busy multilane road (e).

Subjects riding the skateboard were presented a single task (Figure 3) and not asked to enter motorized traffic. It started entering the Marienplatz. At first, they were confronted with pedestrians (a) and an obstacle, a set of stairs (b). Then they had to move through the same outdoor catering of restaurants and cafes as the cyclist group and finally entered a long stretch all along the square.

5.2 Questionnaire

After completion of the experiments, all test persons were asked to fill out a questionnaire. The questionnaire consisted of 21 questions addressing usability, perception, suitability, and demographic background. Users could answer the Likert-scale questions on a scale from 1 (totally disagree) to 4 (totally agree). In addition, some questions were open-ended.

6 RESULTS

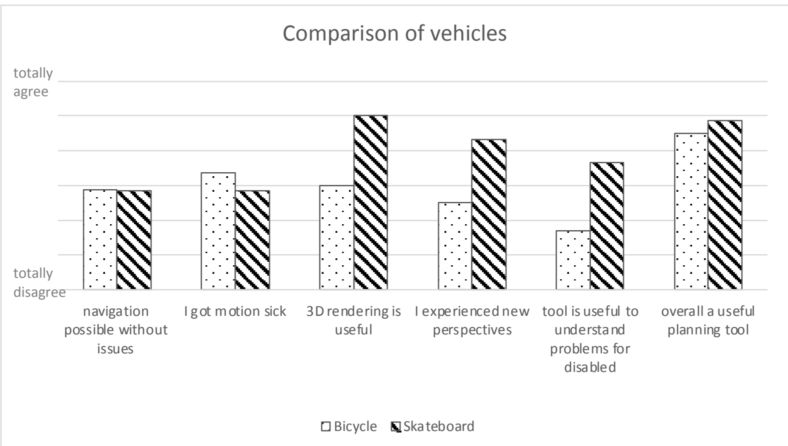
23 people participated in the experiments. 16 used the virtual bike, seven the virtual skateboard. In the questionnaire, people highlighted the well-mirrored details of buildings and the overall vast extend of the virtual world. Also, the concept of using the simulators to assess situations and improve public space was rated high (3.3). However, the capability of creating awareness for the needs of people with disabilities strongly depended on the employed vehicle (1.8 – 2.8). Also, the training phase was considered important (3.4) independent of previous experience with VR. Motion sickness was partially occurring (2.6).

In the open-ended section, a common negative remark referred to a problem with the steering of the bike. This only occurred on one of the test days and has been fixed. Another negative feedback, which was also expressed in other sections of the survey, was the lack of realism in the visualization. While buildings and objects were detailed enough to be recognizable, the lack of ground texture detail was seen as a particular shortcoming. Also the surfaces of the model were not smooth enough in some places. Curbs which can be passed under some circumstances and other obstacles (railings and buildings) which can never be passed are not treated differently which led to confusion and unrealistic behavior.

The comparison of the responses regarding the vehicles and their usability revealed that the skateboard simulator was rated as better overall than the bicycle. Especially the suitability of the simulator was graded as good (3.2) for the skateboard simulator and rather poor for the bicycle (2.4). However, the functionality of the navigation was ranked equally for both devices (2.4). Only few subjects regularly use a skateboard (1.1) while a lot use the bicycle regularly (3.4).

Loss of control over the skateboard was quite common, either in the way of hitting a wall and bouncing back or overcompensation in steering leading to an unwanted oscillation.

Although the tasks performed on the skateboard were shorter in time, motion sickness was also reported similarly (bicycle 2.6, skateboard 2.4).



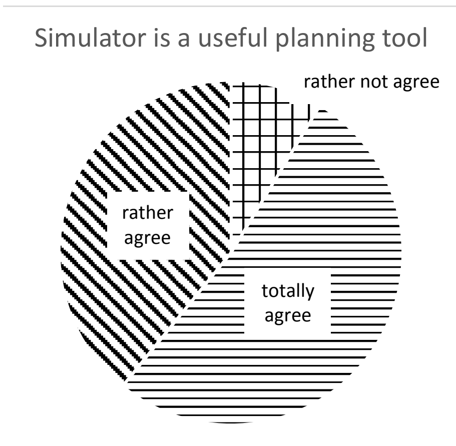


Figure 4 (left): Comparison of vehicles and agreement of users by category. Figure 5 (right): Overall suitability of the tool.

We decided to omit to wheelchair at this stage of the tests. The reason for this was that earlier testing proved that using the wheelchair is particularly peculiar for people unfamiliar with it, as the speed of movement is relatively slow. Although it is equivalent to the speed of a real wheelchair, it appeared slower to the users. This may be explained by the fact that none of the subjects had comparable experience in using wheelchairs relative to the other vehicles.

7 CONCLUSION & OUTLOOK

The study has shown that simulators are considered a useful tool, although a lack of realism was criticized. We conclude that a higher level of detail in the visualization may therefore be an optional addition rather than a requirement to success in the applications described. The simulators allow testing of existing real-world environments and planning for future urban design in virtual realities. They also enable a playful approach to complex topics and raise awareness of limitations in public space.

As mentioned in the Implementation chapter, the bicycle simulator showed some shortcomings. Therefore, new solutions have already been developed to remedy the problems and provide a better immersive experience. A different framework is now used that is not based on direct contact between the rear wheel or tire and the roller. Experiments with the new hardware have yet to be repeated.

For the wheelchair, an option in this setting would be to use more profiled tires to improve grip. A promising force feedback was added, but the implementation of vehicle dynamics was not completed yet. As stated earlier, studies with the wheelchair simulator also still need to be conducted.

In general, the simulators are still under development and can be improved and stabilized. However, the current status allows the assessment of many key aspects. We will continue to address the identified challenges and perform further experiments. Work in the near future will include improved ground texture and surface, tuning and improving the simulators' hardware and implementing improved vehicle dynamics. The tasks in further studies (including their length and intermissions) will be based on the results from this study.

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