Abstract

Using virtual reality (VR) for environmental evaluation is one of the innovations in planning process to support the involvement of local population in decision making. The power of VR in public participation is further enhanced by its application online. However, current online VR applications for public participation is mostly restricted as visualisation tools. Evaluation of the virtual sound environment is rarely supported. This study developed a demonstrator tool of web-based online VR for participatory evaluation of urban sound environment. Piazza Vittoria in Naples, Italy was used as the case site to create the virtual environment. The tool employed affordable visualisation and auralisation for the general public to use online in mainstream web browsers with their own devices. The tool was tested online and the results were analysed to discuss the applicability, potential and challenges of online VR for participatory evaluation of urban sound environment.

1. Introduction

Virtual reality (VR) has been intensively investigated and employed as a technology to present proposed urban development in intuitive and interactive ways. It allows policy makers and local communities, as well as urban planners themselves, to experience and to better understand the changes in the concerned environment before the development takes place, and thus to enable information sharing and consensus building throughout the planning process (Axford et al., 2007; Engel & Döllner, 2012). With the rapid development in information and communication technologies in recent years, the power of VR in public participation is further enhanced by its application online. The online approach can make VR participation more accessible by making information and participation sessions available at any time and from any locations with internet access, and encourage expression of opinions by providing a non-confrontational atmosphere (Bulmer, 2001). Examples of online VR for public participation can be found in Knapp & Coors (2008), Smith et al. (2012), Weber et al. (2009), Zhang & Moore (2014), etc. These studies show that online VR has opened up new forms of communication, interaction and collaboration for participatory decision-making in urban planning.

However, nearly all the current online VR applications for public participation are developed as visualisation tools to involve the public in decisions solely on the visual environment, or only provide audio stimuli as add-on effects lacking authentic references to the virtual scenes. Sound environment is of vital importance to a liveable and sustainable urban environment.

Action plans are required in European cities to address noise issues and to reserve quiet areas (European Parliament and Council, 2002). Recently, strategies are being extended from noise control to design of sound environment, with acoustic interventions to be made throughout the planning process (Alves et al, 2015). Online VR tools that promote participatory evaluation of urban sound environment will be highly beneficial for this initiative of urban sound planning.

On the other hand, potential of offline VR for participatory evaluation of sound environment has been widely studied (Stienen&Vorländer, 2015). VR has shown advantage in scenario control for comparative presentations of ante-operam, post-operam (Ruotolo et al., 2013) and alternative scenarios (Bastürk et al., 2011; Echevarria Sanchez et al., 2017; Maffei et al., 2013a, 2013b), and advantage in ecological validity for multisensory evaluation of urban sound, visual and global environments that highly congruent evaluation results in VR and on-site can be achieved (Maffei et al., 2015).

Several factors might have discouraged attempts on online VR for participatory evaluation of urban sound environment. Firstly, computational load of real-time rendering of spatialised sound for complex urban environment can be prohibitively high (Maffei, 2012; Stienen & Vorländer, 2015), and this issue can be more intractable in cases of online applications. Secondly, databases of sound sources and boundary conditions for auralisation of outdoor environment are not yet available in standardised formats. Thirdly, sufficient control over online participants' audio hardware and playback settings can be hard to achieve (Pedersen et al. 2012). Last but not least, urban sound planning approaches do not yet have a significant impact on the planning discipline, and interests in promoting public participation in related processes are still relatively low (Easteal et al., 2014).

As an initiative attempt, this study developed a demonstrator tool of web-based online VR for participatory evaluation of urban sound environment, and tested the tool online to explore the applicability, potential and challenges of such tools.

2. Methods

2.1 Design concepts

For evaluation of large urban environment, the demonstrator tool should allow free movement of participants inside the presented virtual environment. While on the other hand, a fundamental requirement of the tool was that the computational load should be low enough to run on general home computers. It was thus necessary to consider less demanding rendering processes and simplify the content of the virtual environment as much as possible within acceptable quality limits. Headphones, instead of dedicated or built-in speakers, were suggested for audio playback. For one reason, with the use of headphones it would be easier to control how the spatialised sound would be played by each individual participant; for the other, headphones are widely available and commonly used at home or work (Lindquist, 2014). The tool was also conceived to be web-based. The web-based solution would further constrain VR complexity due to limits in browsers' memory space. However, it would be easier for potential participants to use without the hassles of downloading and/or installing any applications, and thus to promote participation. Following these concepts, Figure 1 shows the workflow of the tool development, which is detailed in the following sections.

2.2. Visualisation

Piazza Vittoria (40°49′56.53″N; 14°14′28.37″E), an urban square in Naples, Italy, was chosen as the case site for the demonstrator tool. The square is about 70 m × 150 m in size and is adjacent to the seafront. It serves as a popular gathering place for locals and tourists, but also as an important node of the city road network.

With GIS data of the site obtained from www.archweb.it and photos taken during on-site surveys, 3D models of objects for the virtual environment were created using AutoCAD 2012, SketchUp 8 and 3ds Max 2012, and finally assembled and rendered in Unity 5.3. Modelled objects included buildings, roads, pavements, street furniture, fountains (3D Warehouse, 2016a, 2016b), vegetation (partly from Unity Asset Store, 2016), vehicles and people (3D Warehouse, 2016c). Buildings were geo-specifically textured using edited building facade photos taken on site, while other elements were textured using images from existing texture database. Vehicles were animated for two traffic scenarios: a scenario of an approximation of on-site observations and a scenario that removed current traffic restrictions. Figure 2 illustrates the traffic flows and volumes in these two scenarios. Vehicle speeds varied from 20 km/h to 50 km/h depending on road segments and were reduced at turnings. Table 1 lists the detailed parameters of the animation. Only passenger cars were used due to difficulties in producing source sounds of vehicles of other types.

Some measures were taken to ensure smooth running of the demonstrator tool. High resolution textures were avoided and animations were compressed to reduce the sizes of Unity files, and thus to keep reasonably short loading time of the tool and low memory usage inside web browsers. Diffuse shader, a relatively computationally cheap Unity built-in shader, was used for graphical rendering, since GPU of participants' devices would vary and some may not be able to perform more advanced graphical renderings.

2.3. Auralisation

Sound elements added to the virtual environment included vehicle sound, bird sound, fountain sound, sea wave sound, human voice, and background urban sound. The following sections describe how these sounds were produced, rendered and calibrated.

2.3.1. Synthesis of car source signals

Vehicle sound in this demonstrator tool consisted of tire noise and propulsion noise. Due to the difficulty in acquiring the sound at source by recording, synthesised sound was used.

The synthesis was a simplified version of the emission model of the auralisation model of accelerating passenger cars presented in Pieren et al. (2016). For this demonstrator tool, only one single car type (specific tire and engine) was synthesized and no individualisation was made. For tire noise, the pink noise was generated in ITA-Toolbox (Berzborn et al., 2017). Road surface correction and directivity were not taken into consideration. For the tonal component of the propulsion noise, constant product of gear and axle ratios and constant engine order sound pressure levels were used. The product of gear and axle ratios was 15, assuming all cars were in the second gear for speeds $\leq$ 50 km/h. Values for engine order levels were extracted from Fig. 13(b) in Pieren et al. (2016) measured at full load and 3000 rpm, which was a compromised choice concerning data availability and suitability. For a more realistic simulation for this study, measurements at medium loads and lower rpms would be more appropriate. Only up to order 10 was simulated due to too many high-frequency parts for the synthesised propulsion noise found with higher orders. For the noise component of the propulsion noise, the model for tire noise was used but with data from Table II in Jonasson (2007), due to lack of data for this part of synthesis in Pieren et al. (2016). However, it should be noted that the data from Jonasson (2007) were for the total level of the propulsion noise (tonal + noise). To use them as for noise component only, a subjectively determined reduction was made to balance the level ratios of the tonal and noise components.

Synthesisers for the tire noise signals and the propulsion noise signals were implemented in MATLAB 2016a. These signals were pre-rendered. The obtained tire noise signals and propulsion noise signals were then added to produce source signals of individual cars. 14 source signals were produced, corresponding to the 14 paths used in traffic animation (Table 1). Cars on the same path used the identical source signal for the path. Fade-in and fade-out effects were applied to each signal.

2.3.2. Recordings of other sounds

Other sounds, including human voice, bird sound, fountain sound, sea wave sound and background urban sound, were produced based on recordings.

For human voice, samples of chats in Italian involving 2 to 5 people were recorded using a Zoom H6 recorder and a Soundfield SPS200 microphone in an anechoic chamber. For background urban sound, samples varying in levels of traffic noise were recorded using the same equipment at locations around Piazza Vittoria. Samples of bird sound, fountain sound and sea wave sound were obtained online in WAV format from Freesound.org (2016a, 2016b, 2016c).

Because sound clips in Unity need to be mono for sound positioning, only a single channel of each of the acquired multi-channel recording samples were used. The extracted samples were clipped and edited to reduce sizes, remove interruptive noise, and allow seamless loop.

2.3.3. Spatial rendering of sounds

All the sound files were imported into Unity and attached to corresponding objects. The attached sounds were spatially rendered in real time by Unity's built-in sound engine.

Vehicle sound, human voice, bird sound and fountain sound were treated as point-source sounds, and sound attenuations were applied with a logarithmic volume-distance rolloff, corresponding to a 1/r sound pressure dependence of a point source in free field. Sea wave sound and background urban sound should be treated as area- or quasi-area-source sounds, but in Unity they were attached as point objects. To address this issue, it was decided to apply linear volume-distance rolloff for their attenuations, with proper positioning of the sound objects, to simulate the more ambient yet still directional sound emissions.

Spatialisation was applied simply by Unity's built-in panning, which took the source and regulated the gains of the left and right ear contributions based on the distance and angle between the source and the receiver. This provided simple directional cues on the horizontal plane. With the Unity Audio Spatializer SDK (5.2 feature), it was possible to implement HRTF filtering based on publicly available data sets such as KEMAR. However, the rendering was not smooth for a large number of fast moving objects.

Doppler effect was applied using the default setting in Unity, which changed the pitch of the sound according to the relative speed of the source and the receiver. Sound reflection was not considered for this open square case site, since it was not supported by the Unity sound engine and would dramatically increase computational load even if achieved by third party audio extensions.

2.3.4. Adjustment of sound levels

Emission levels of car sounds, i.e., the levels of car source signals, were calculated in synthesis and were not adjusted in Unity. Emission levels of other sounds were adjusted in Unity relative to car sounds as heard inside the virtual scenes.

To do this, the headphone reproduction system needed to be calibrated first. A standard approach for this could be calibrating the playback level of one of the car source signals to its synthesised level using a head and torso simulator. However, a subjective approach was used in this study. In this subjective approach, a male speech sample was played back through headphones, and the audio volume of the computer was adjusted by the researchers until the playback sounded as loud as normal speech in a quiet room. The male speech sample was recorded in the same manner as the recording of human chats, and was calibrated to 60 dB L_{Aeq} using car source signals as references. 60 dB L_{Aeq} was chosen since this was reported to be a typical male speech level in general conditions (Olsen, 1998). This subjective approach was used, since generally high accuracies in level adjustment could be achieved (Pedersen et al. 2012), and since it would also be the approach by which participants were to calibrate their devices for the online tests (Section 2.4).

After the playback setting, Researchers who were familiar with Piazza Vittoria navigated inside the virtual scenes to adjust the emission level of each sound except car sounds. This process of level adjustment relied largely on researchers' experience and perception.

2.4. User interface and the online test

Along with the visual and audio contents, user interface and evaluation tasks were configured in Unity. Upon the start, a short description of the demonstrator tool was given to the participants, followed by questions for their demographic information. The next step was to calibrate participants' audio devices. This was achieved by playing the male speech recording sample used in Section 2.3.4 and asking participants to put on their headphones and adjust the audio volume of their computers until the playback sounded as loud as normal speech in a quiet room. When they were ready, they clicked to enter the virtual scene of Piazza Vittoria, and were instructed to use WASD keys to move forward, left, backward and right, and use the mouse to control direction. By performing five simple tasks, participants explored the virtual piazza and evaluated the sound environment. A description of the five tasks can be found in (Author info, 2016). The tasks demonstrated a variety of possible forms of participation tasks. Finally, participants were asked to rate their 'VR experience' by rating the 'quality of the virtual visual environment' and the 'quality of the virtual sound environment' on 7-point scales (from 'poor and unrealistic' to 'good and realistic'), and leave whatever comments that they had on the tool. All the participants' inputs were logged and maintained in an online database. Performance of their computers were captured in terms of frame rates in frames per second (FPS) during each task.

The demonstrator tool was released in forms of a WebGL game and a Unity Web Player game in September 2016 for an online test. The WebGL version can be opened and used directly in most popular web browsers (e.g., Firefox, Chrome, Safari, but not Internet Explorer). The Unity Web Player version provides higher visual and audio rendering qualities, but requires users to install a small plug-in called Unity Web Player (size: 12 MB) beforehand. It was left to each participant to decide which version to use. Invitations for the online test were disseminated via online social media and emails to local communities of Naples, as well as to researchers and practitioners in the fields of urban planning and acoustics.

3. Results and discussion

By 24 October 2016, 100 valid responses to the online test were received. Substantially more participants were from the younger generations (18-35 yrs: 82%; 36-65 yrs: 16%). Most participants (62%) were willing to install the small plug-in to use Unity Web Player version for higher VR quality, and most participants (81% with Unity Web Player and 61% with WebGL) enjoyed frame rates above 30 FPS. Tasks to evaluate the sound environment of Piazza Vittoria were mostly properly performed. Figure 3 illustrates ratings of the VR quality given by the participants. It shows that most participants (62%) rated the visual part as relatively good and realistic with rating scores equal to or above 5 (Mean = 4.73; S.D. = 1.52). More neutral ratings were given to the sound part with about half of the participants (51%) rated it as relatively good and realistic (Mean = 4.36; S.D. = 1.61).

34 participants left comments at the end of the test. Many of the comments were on the sound part, and the acoustic jargon appeared in some comments indicates a high involvement of acousticians. Some mentioned that the car sounds were not realistic enough and had too much energy in the low frequencies. This could be due to the fact that the engine orders were synthesised from full load measurement data. Some thought that the virtual sound environment was too simple and should have more sound sources with more variations. This might partly be attributed to the lack of individualisation in car source signal synthesis. Some thought that the relative levels of different sounds could be better adjusted especially that the car sounds were too dominating. There were also reports on other sound issues such as "clicking noise", not enough sound attenuation, etc. Less comments addressed the visual part and general usage issues. Similar to the sound part, some participants thought that more environmental elements (e.g., poles, bins and dynamic skybox) and variations (e.g., people's activities, vehicle types and movements) should be introduced. Others commented on human model realism, movement control, evaluation tasks, etc. Apart from the above criticism and suggestions, many participants expressed that the web-based demonstrator tool was an innovative and encouraging step towards efficient and effective participatory decision-making in urban sound planning.

Results of the online test show high potential of online VR to provide virtual visual and sound environments of decently high quality for participatory evaluation of urban sound environment, in a convenient and cheap manner for both the participants and the developers. Both the WebGL and Unity Web Player versions could run properly, suggesting that online VR configured as this web-based demonstrator tool is feasible on devices of general public users. Possible improvements in auralisation quality might be made by introducing more sound sources with more variations and by increasing the realism of synthesised sounds. When introducing more sound sources, it might be necessary though to prioritise the sound sources (Hell et al., 2016) to avoid the number of active sounds exceeding possible system limits and to reduce computational load. Individualisation in car source signal synthesis with car- and scenario-dependent parameters can increase both sound variation and realism, which however would require a substantial amount of data measurements. Providing binaural technology with HRTF filtering and more accurate sound propagation with e.g. reflection and ground absorption, would also increase sound realism and immersion. However, challenges on computational load must be considered. For many of these improvements, standardised database of sound sources and boundary conditions for urban environment will be highly beneficial.

4. Conclusions

This study developed a demonstrator tool of web-based online VR for participatory evaluation of urban sound environment. Piazza Vittoria in Naples was used as the case site to create the virtual environment. Both synthesised and recorded sounds were used and rendered in computationally cheap ways for auralisation. The tool was tested online and the results show high applicability of online VR for participatory evaluation of urban sound environment. The auralisation quality can be improved with more sound sources and variations, more realistic sound synthesis, and more advanced sound rendering.

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Table 1. Traffic animation parameters (ZTL: in the scenario with traffic restrictions)

		Section 1	Section 2	Section 3	Section 4	Section 5	Section 6	Section 7	Section 8	Section 9	Section 10	Section 11	Section 12	Section 13	Second 14	No. of loops every 120 s	No. of cars assigned
Path 1	Speed (km/h)	50	50-20	20-35	35	35-25	25-50	50	-	-	-	-	-	-	-	1	3
	Starting time (s)	0	3.7	5.5	7.2	14.5	16.7	18.7	31	-	-	-	-	-	-		7 (ZTL)
Path 2	Speed (km/h)	50	50-25	25-35	35	35-30	30	30-40	40-25	25	25-50	50	-	-	-	1	3
	Starting time (s)	0	3.7	5.7	7.4	10.6	13	18.8	21	23.2	24.2	28.2	45	-	-		
Path 3	Speed (km/h)	50	50-20	20-30	30	30-15	15-30	30	30-40	40	40-25	25	25-50	50	-	1	3
	Starting time (s)	0	3.7	5.6	7.2	14.4	16.2	18	23	24.8	25.3	27.1	28.5	32.5	48		
Path 4	Speed (km/h)	50	50-25	25-35	35	35-25	25-35	35	35-25	25-50	50	-	-	-	-	1	7
	Starting time (s)	0	3.5	5.5	7.3	13.8	15.5	17.3	23	24	27	59	-	-	-		0 (ZTL)
Path 5	Speed (km/h)	50	50-30	30-40	40	40-25	25	25-35	35-25	25-50	50	-	-	-	-	1	3
	Starting time (s)	0	17.4	19.5	21	23.7	25.3	40.7	46.1	48	51	82	-	-	-		0 (ZTL)
Path 6	Speed (km/h)	50	50-30	30-40	40	40-25	25	25-20	20-30	30	30-20	20	20-50	50	-	1	3
	Starting time (s)	0	17.4	19.5	21	23.7	25.3	37.9	40	41.8	48	49.8	50.5	53.5	85		0 (ZTL)
Path 7	Speed (km/h)	50	50-35	35	35-40	40	40-30	30	30-50	50	-	-	-	-	-	2	3
	Starting time (s)	0	19	20.7	21.5	22.7	25.3	27.7	35.2	39.1	51	-	-	-	-		10 (ZTL)
Path 8	Speed (km/h)	50	50-35	35-40	40	40-25	25	25-40	40	40-30	30	30-50	50	-	-	2	3
	Starting time (s)	0	19	21.5	22.5	24.7	27.3	31	33.7	36	37.8	38.8	41.8	58	-		
Path 9	Speed (km/h)	50	-	-	-	-	-	-	-	-	-	-	-	-	-	2	10
	Starting time (s)	0	56	-	-	-	-	-	-	-	-	-	-	-	-		0 (ZTL)
Path 10	Speed (km/h)	50	50-25	25-35	35	35-25	25	25-50	50	-	-	-	-	-	-	2	3
	Starting time (s)	0	16.6	19.2	21	23.5	25	35.9	42.3	53	-	-	-	-	-		4 (ZTL)
Path 11	Speed (km/h)	50	50-30	30-40	40	40-25	25	25-50	50	-	-	-	-	-	-	3	4
	Starting time (s)	0	9.7	11.8	13.6	24.5	26	27	30	40	-	-	-	-	-		
Path 12	Speed (km/h)	50	50-30	30-40	40	40-25	25	25-50	50	-	-	-	-	-	-	3	5
	Starting time (s)	0	9.7	11.8	13.6	24.5	26.3	27.3	30.3	40	-	-	-	-	-		
Path 13	Speed (km/h)	50	-	-	-	-	-	-	-	-	-	-	-	-	-	3	2
	Starting time (s)	0	33	-	-	-	-	-	-	-	-	-	-	-	-		
Path 14	Speed (km/h)	50	-	-	-	-	-	-	-	-	-	-	-	-	-	3	2
	Starting time (s)	0	35	-	-	-	-	-	-	-	-	-	-	-	-		

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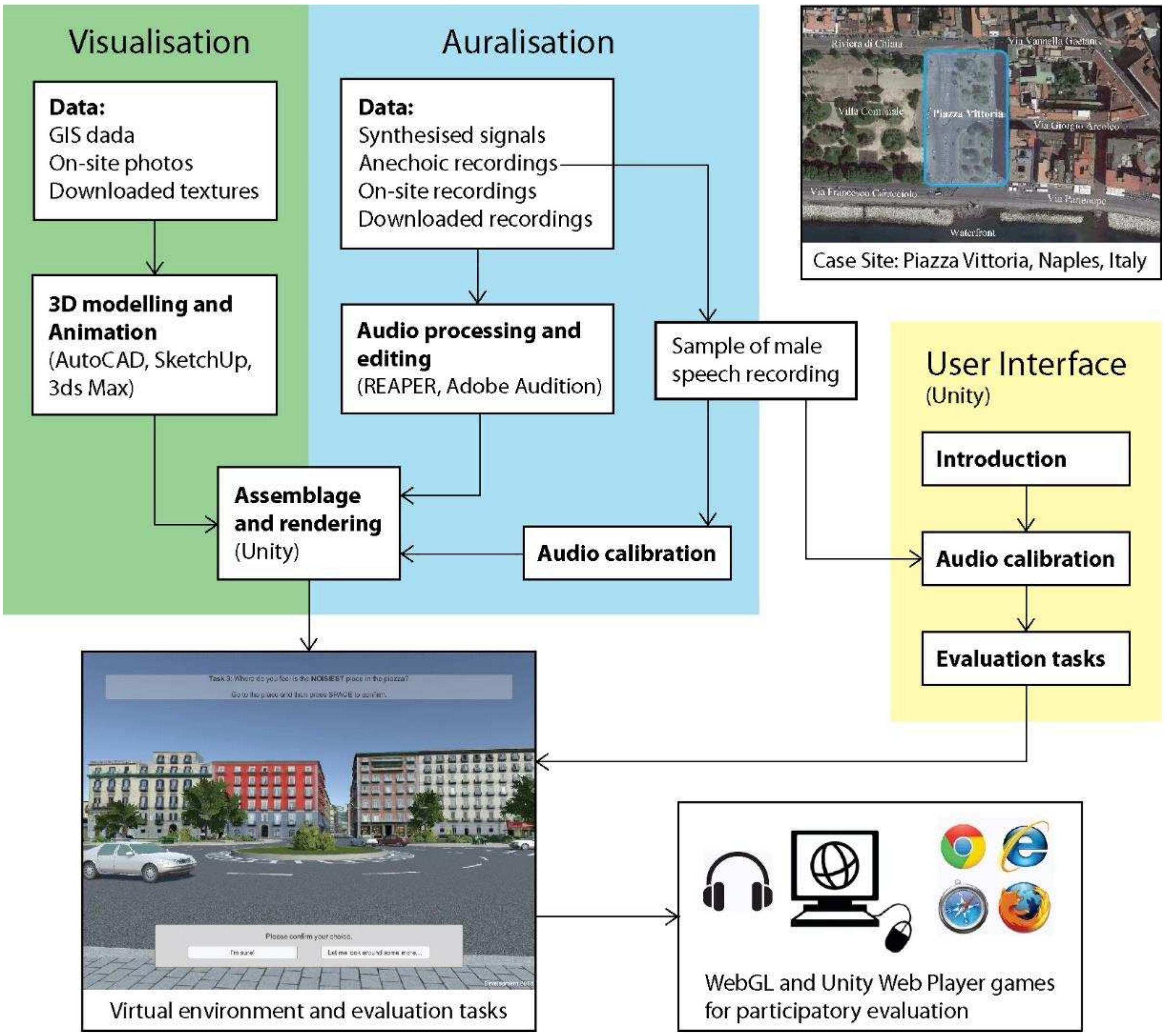

Figure 1. Workflow of the development of the demonstrator tool.

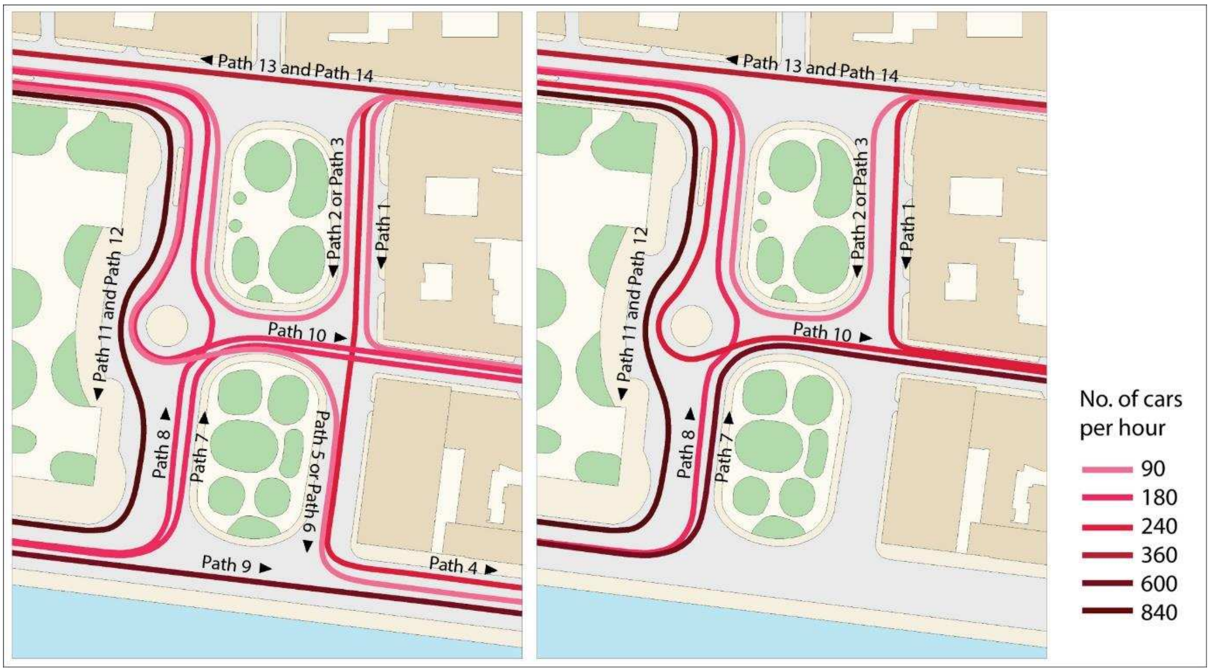

Figure 2. Traffic flows and volumes in the two scenarios. Left: without current traffic restrictions, right: with current traffic restrictions.

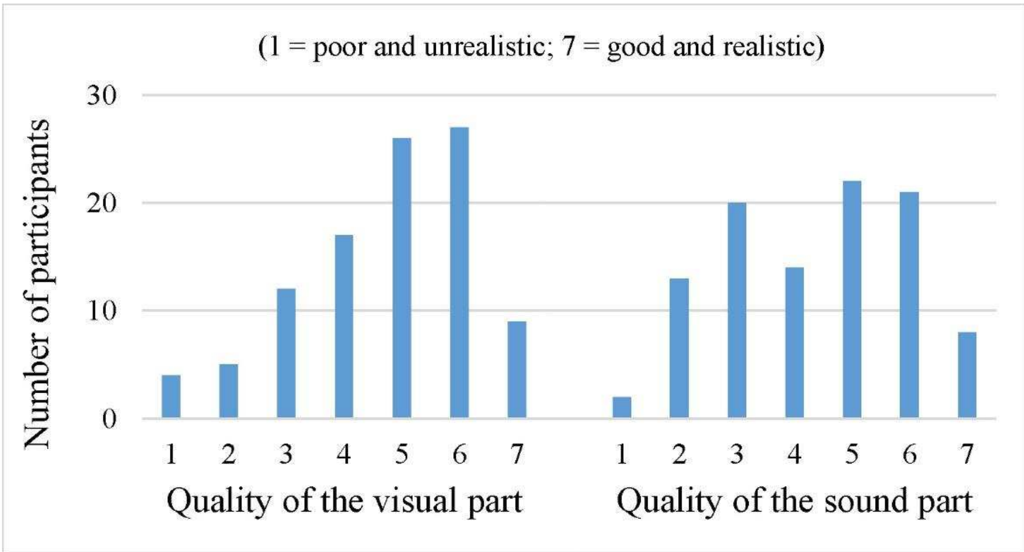

Figure 3. Ratings of the VR quality.