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How do shared-street design and traffic restriction improve urban soundscape and human experience? —An online survey with virtual reality

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Abstract

Sound, together with other sensory impressions, contributes to the perceived quality of the global environment, and influences human experience of the place. This study investigates how shared-street design and traffic restriction, two widely used street management measures in urban areas, influence urban soundscape and human experience of the place, by asking: 1) Do shared-street design and traffic restriction improve the urban soundscape? 2) In different street management scenarios, how relevant is the soundscape to human experience of the place? By means of an online virtual reality application, two street-design scenarios and two traffic-restriction scenarios were simulated, and a task-based online survey was carried out to obtain participants' responses to the simulated virtual scenarios. The results show that shared-street design made the soundscape calmer and traffic restriction made the soundscape more pleasant. There was also potential interaction between shared-street design and traffic restriction that shared-street design might lead to changes in soundscape pleasantness depending on traffic restriction. High relevance of soundscape to human experience of the place is indicated, that peoples' perception of the acoustic environment and preferences for the acoustic environmental elements contributed to their preferences for places. However, the relevance might be relatively lower in shared-street scenarios.

Keywords: soundscape; shared street; traffic restriction; virtual reality; online survey

1. Introduction

Soundscape, as defined by the International Organization for Standardization, is the "acoustic environment as perceived or experienced and/or understood by a person or people, in context" (ISO, 2014). Sound, together with other sensory impressions, contributes to the perceived quality of the global environment, and influences human experience of the place (Southworth, 1969). Over the past two decades, there has been a growing interest in soundscape and efforts were made to develop methods of acoustic design to improve soundscapes (Aletta et al., 2016; Brown & Muhar, 2004; De Coensel et al., 2010; Kang et al., 2016). However, applications of acoustic designs can sometimes be very constrained due to limited control over existing environmental sounds, and thus actions specifically proposed to improve the soundscape may appear impractical, especially in some places in cities where dominant sounds of traffic, people and commercial activities are part of the vibrancy (Brown & Muhar, 2004).

On the other hand, some street management measures that are popular and typical for vibrant urban areas, although not initiated for acoustic purposes, might be able to improve the soundscape in indirect manners.

One example of street management measures that has such potential is shared-street design. Shared-street design aims to reduce dominance of motor vehicles, which is common on conventional roads, and promote pedestrian and cycling activities that use the street as a “place” in addition to its mobility and access purposes as a “road” (Karndacharuk et al., 2014). Key features of shared streets include mixed use of street spaces by motor and non-motor traffics with little physical separation or regulatory control, homogenised pavements of zones that otherwise differentiate as sidewalk and carriageway, and where appropriate, street furniture and facilities that encourage multiple social activities (Hamilton-Baillie, 2008; Karndacharuk et al., 2014). Shared-street design has been applied in busy urban areas in many cities (e.g., Jaffe, 2015; Shared Space, 2005; Vasisht & Karndacharuk, 2016). It has been shown that shared streets have higher levels of safety and comfort (Ruiz-Apilánez et al., 2017; Vasisht & Karndacharuk, 2016), yet efficiencies for mobility and access, even of motor vehicles, are still maintained (Hamilton-Baillie & Jones, 2005; Karndacharuk et al., 2015). Apart from these well-recognised benefits, shared-street design may also influence soundscape with changes in the acoustic environment caused by probable changes in traffic dynamics (Bérengier, 2002) on the street. Moreover, the transformed streetscape may alter people’s perception of the soundscape due to aural-visual interaction in environmental perception (Jiang & Kang, 2016; Viollon et al., 2002).

Some street management measures will have more direct and stronger influence on soundscape, for example, traffic restrictions. Traffic restrictions are regulatory controls on access of motor vehicles to parts of the road network (Jones & Hervik, 1992). There are varied degrees of restrictions, from limited access of vehicles of certain categories at certain time periods to permanent and complete ban of motor vehicles (Jones & Hervik, 1992). Traffic restrictions are implemented in many cities over the world, aiming to mitigate traffic congestion in urban centres and reduce environmental pollutions especially air pollution (e.g., Bontempo et al., 2014; Cheshire et al., 1998; Holman et al., 2015; Wu et al., 2010). Traffic restrictions are also common in sensitive urban areas to help preserve the historical, cultural and/or commercial values (e.g., Gunnarsson, 1993; Lu et al., 2003). Whether noise control is the concern or not, traffic restrictions will be quite effective in altering the acoustic environment due to resulted changes in traffic volume and/or composition, and thus they influence the soundscape of the area.

Other street management measures, such as traffic calming (Harvey, 1992), self-explaining roads (Charlton et al., 2010) and road diet (Huang et al., 2002), can also have influences on soundscape. These measures typically have more physical interventions to discourage vehicle movement than shared-street design does, yet do not disable vehicle movement completely like traffic restriction. Influences that these measures can have on the soundscape may thus vary in between those of shared-street design and traffic restriction.

However, currently there is a lack of empirical studies on how these street management measures influence soundscapes, and how the shaped soundscapes contribute to human experience of the place. Findings of such studies will supplement knowledge not only of soundscape design in vibrant urban areas, but also of human-centred place-makings in broader contexts.

Therefore, this study aims to make an empirical investigation on how shared-street design and traffic restriction, contrasting in associated changes in visual streetscape and acoustic environment, influence urban soundscape and human experience of the place. Specifically, by using an online virtual reality tool for task-based evaluation of urban sound and global environments, this study aims to answer: 1) Do shared-street design and traffic restriction improve the urban soundscape? 2) In different street management scenarios, how relevant is the soundscape to human experience of the place? Improvement of soundscape will be measured by comparing multiple dimensions of soundscape perceptions between the scenarios (see Task 1 in Section 3.3); while relevance of soundscape to human experience of the place will be analysed by comparing location preferences against noise perceptions and by comparing environmental factors that contribute to the location preferences (see Task 2 – Task 5 in Section 3.3).

Section 2 of this paper provides a methodological introduction to virtual reality and online survey that were used in this study. Section 3 describes in detail the experimental design and implementation. Section 4 presents the results and Section 5 discusses the results in response to the research questions. Section 6 concludes the paper.

2. The use of virtual reality and online survey

2.1. Virtual reality

Virtual reality (VR) is a 3D user-computer interface that generates a real or imaginary environment and simulates in real-time the user's presence in this environment through multiple sensorial channels (Burdea & Coiffet, 2003). Since the 1990's, VR has been widely used for environmental preference studies (Smith, 2015). While a majority of these studies were visual-oriented and based on VR applications only capable of real-time visualisation (e.g., Bateman et al., 2009; Bishop et al., 2001; Bishop et al., 2009), recent development in auralisation technology and increasing interest in soundscape have enabled and encouraged a growing number of multisensory environmental preference studies based on VR applications capable of real-time aura-visualisation (e.g., Baştürk et al., 2012; Maffei, 2012; Smyth et al., 2010; Stienen & Vorländer, 2015). Advantages of VR for such studies are realistic presentation of and sufficient control over environmental stimuli at reasonable cost (Maffei, 2012; Smith, 2015). Its ecological validity was tested in Maffei et al. (2016) which compared human cognitive and affective responses in VR and in situ, and found good levels of congruence.

Since comparable before-after street scenarios are desirable but hard to achieve in reality for preference studies (Ruiz-Apilánez et al., 2017), this study used VR for environmental representation. It was conceived to allow free movement of participants inside the presented virtual environment and provide real-time aura-visualisation. It should be noted, however, although immersive head-mounted-display and motion-track were readily achievable with the construct of the VR tool used in this study, the VR tool would be used online with participants' own devices (see Section 2.2), so the more widely available computer monitors and mice and keyboards were suggested for visual display and navigation.

2.2. Online survey

Over the past two decades, online visualisation has been rapidly developed and widely used for environmental preference studies (e.g., Bishop, 2012; Fu et al., 2005; Smith et al., 2012; Zhang & Moore, 2014). It has been shown that generally reliable landscape perceptions can be achieved with online visualisation (Roth, 2006; Wherrett, 2000). Online auralisation is less common than online visualisation, but has also shown high potential for environmental preference studies (e.g., Finne & Fryd, 2016; Lindquist et al., 2016; Pedersen et al., 2012).

Benefits of online surveys, compared to those in traditional workshop or laboratory settings, are that they can reach much wider participants in more convenient manners and encourage expression of opinions by providing a non-confrontational atmosphere (Bulmer, 2001). However, care must be taken over potential biases in participation, since it will be affected by accessibility to required facilities and habit of internet use (Roth, 2006). There are also issues such as lack of audio and visual display control, absences of staff supervision, mediation and assistance that need to be considered (Lovett et al., 2015).

This study used online survey. The survey was embedded in virtual reality, and it was task-based instead of in the form of more conventional questionnaires, to simulate real-life tasks which would allow more immediate and intuitive behavioural and emotional responses of the participants to the presented environment (Stauskis, 2014). Using online survey would allow participants to have their own time controls on experiencing the virtual environment and performing the survey tasks, and help to achieve a larger sample size. In addition, it is also an innovative attempt of soundscape research in response to the emerging e-participation initiatives in urban planning (Donders et al., 2014).

3. Experimental design and implementation

3.1. Case site and experimental scenarios

Piazza Vittoria, a sea-fronting urban square in Naples, Italy, was chosen as the case site for this study (Figure. 1). The square is approximately 70 m × 150 m in size. It connects the Villa Comunale (an urban park), the historic town and the waterfront of Naples, which makes it a popular place for locals and tourists in the area. At the same time, it receives and directs traffic from the port and several main roads, making it an important node of the city road network. The square provides a soundscape that has the needs and potential to improve. In the past few years, different traffic restrictions have already been tested and implemented in this area to reserve walkability and improve overall environmental quality of the waterfront.

Figure 1. The case site: Piazza Vittoria in Naples, Italy (reproduced based on Google Maps capture). (Greyscale print)

Table 1. The four experimental scenarios.

	No traffic Restrictions (NR)	Traffic Limited Zone on Via Partenope (TLZ)
Existing street design (E)	Scenario E-NR	Scenario E-TLZ
Shared-street design on the east segment of Piazza Vittoria (S)	Scenario S-NR	Scenario S-TLZ

Four experimental scenarios were designed and are described in Table 1. The shared-street design unified pavements of sidewalk and carriageway of the east segment of Piazza Vittoria, and added street furniture and plants on the segment. A comparison of the shared street and its existing counterpart is shown in Figure 2. Traffic and acoustic environment were kept the same between the two street design scenarios. For the traffic restriction scenarios, the TLZ scenario consisted of the traffic restriction plan implemented in the area at the time of this study. The restriction plan closed vehicle entrance of Via Partenope, and traffic moving towards it was reduced and diverted to Via Giorgio Arcoleo. The NR scenario removed the restriction. Traffic flows of the two scenarios were designed based on in-situ observation and estimations. Figure 3 shows the traffic flows with the corresponding noise maps produced in SoundPLAN using the calculation model NMPB-Routes-96. Detailed traffic parameters used for the mapping can be found in Table 1 in Jiang et al. (2018). It should be noted, however, that the calculations of sound emission and propagation in NMPB-Routes-96 were different from those for auralisation in this study (see Section 3.2), nor were sounds other than vehicle sound considered in the noise mapping. Thus, the noise maps were not representations of the virtual acoustic environment to be simulated, but only to illustrate the approximate change in traffic noise caused by traffic restriction.

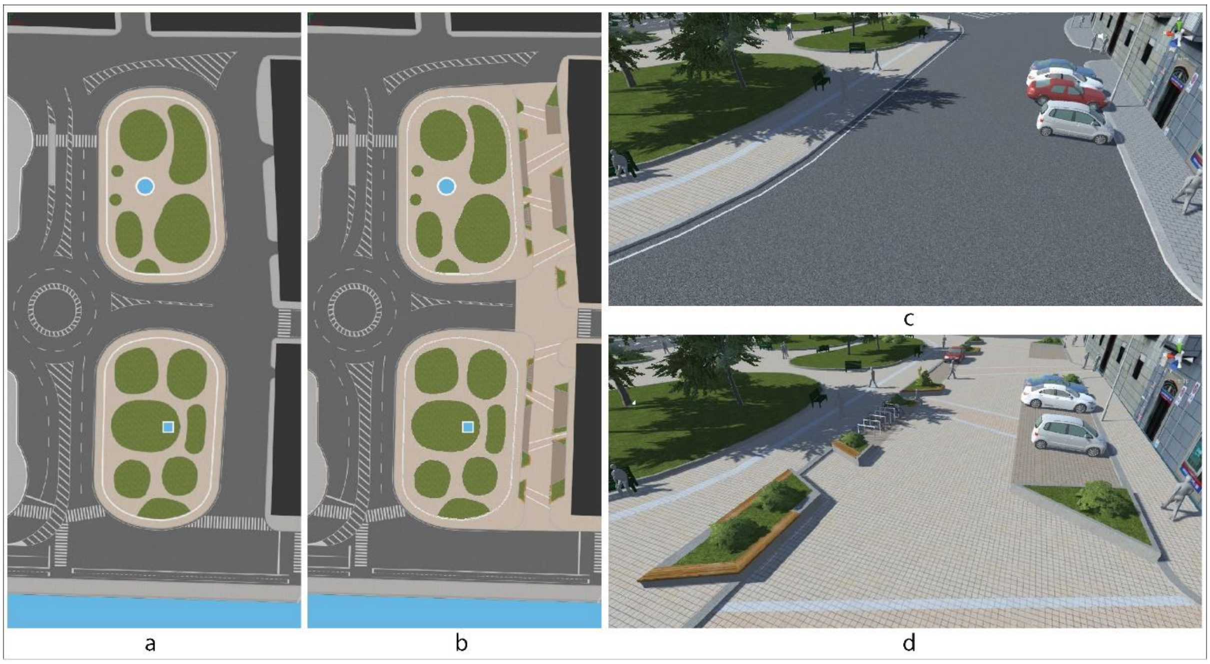

Figure 2. The two street-design scenarios: a. existing streetscape top view; b. shared-street design top view; c. existing streetscape bird's-eye view; d. shared-street design bird's-eye view. (Greyscale print)

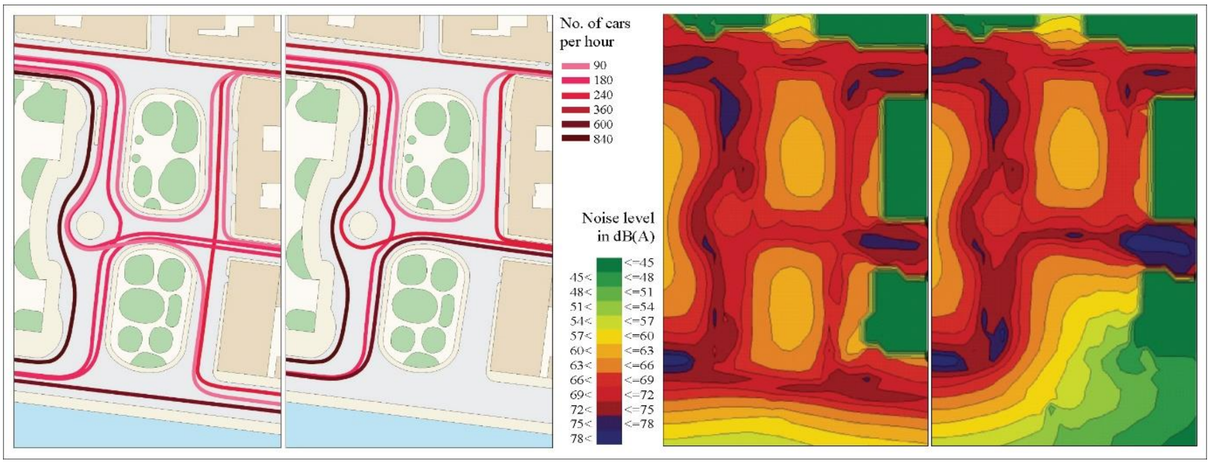

Figure 3. Traffic flows and traffic noise maps in the two traffic scenarios: no-restrictions (left) and Traffic Limited Zone (right). (Greyscale print)

3.2. Visualisation and Auralisation

The virtual scenes of Piazza Vittoria in the four experimental scenarios were created by visualisation and auralisation. A detailed description of the visualisation and auralisation processes can be found in Jiang et al. (2018). This section provides a condensed description.

For visualisation, 3D models of buildings, roads, pavements, street furniture, fountains, vegetation, vehicles and people were created using AutoCAD 2012, SketchUp 8 and 3ds Max 2012, and finally assembled and rendered in Unity 5.3 to visualise the virtual scenes. Buildings were geo-specifically textured using edited building facade photos taken in situ, while other objects were textured using images from existing texture database. Vehicles were animated on constrained paths as shown in Figure 3. The speeds of vehicles varied from 20 km/h to 50 km/h depending on road segments and were reduced at turnings. Detailed parameters of traffic animation can be found in Table 1 in Jiang et al. (2018).

For auralisation, sound elements added to the virtual environment included vehicle sound, bird sound, fountain sound, sea wave sound, human voice, and background urban sound. For vehicle sound, source signals of individual cars were synthesised based on the emission model of the auralisation model of passenger cars presented in Pieren et al. (2016). The emission model was simplified for this study such that it did not consider road surface correction and directivity, nor variations among different car engines and tyres. Thus, only one source signal was produced for each constrained paths used in traffic animations. Source signals of other sounds were produced based on recordings. For human voice, samples of chats in Italian involving two to five people were recorded using a Zoom H6 recorder and a Soundfield SPS200 microphone in an anechoic chamber. For background urban sound, samples of various ambient sounds were recorded using the same equipment in situ 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). Only a single channel of each of the acquired multi-channel recording samples were used.

All the sound files were imported into Unity and attached to corresponding objects. The attached sounds were rendered in real-time by Unity’s built-in audio engine. Vehicle sound, human voice, bird sound and fountain sound were treated as point source sounds, and their attenuations were applied with a logarithmic volume-distance falloff, corresponding to a 1/r sound pressure dependence of a point source in free field. Sea wave sound and background urban sound can be described as quasi area source sounds. After some tests, it was decided to apply linear volume-distance falloff for their attenuations, with proper positioning of the sound objects, to simulate the more ambient yet still directional sound emissions. 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 reflections and air absorption were not considered in this study. The spatialisation was applied 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 between the source and the receiver, and the direction of the source in relative to the receiver. The audio output was stereophonic. Headphones were recommended for audio playback for the online survey purpose, since they are widely available and commonly used at home or work, and with headphones it would be relatively easier, as compared to dedicated or built-in speakers, to control how the spatialised sound would be played by each individual participant.

After the configuration of sound spatial rendering, researchers who were familiar with the Piazza Vittoria navigated inside the virtual environment to adjust the level of each sound except car source sounds of which the levels were already defined in synthesis. This process of level adjustment was subjective, relying largely on researchers' experience and perception. To do the adjustment, the audio volume of the computer in use was first adjusted such that the playback of a 60 dB(A) male speech sample sounded as loud as normal speech in a quiet room. 60 dB(A) was chosen since this was reported to be a typical male speech level in general conditions (Olsen, 1998).

3.3. Survey design and evaluation tasks

Along with the visual and audio contents, the survey interface and evaluation tasks were configured in Unity. Upon the start, an introduction page was shown to give a short description of the experiment, stating that participants "*will explore the virtual scene of*

Piazza Vittoria in Naples, Italy and evaluate the sound environment by performing five simple tasks" (Figure. 4a), followed by a conventional questionnaire page where participants' demographic information was requested (Figure. 4b). The next step was to calibrate participants' audio devices. This was achieved by playing the male speech recording sample used in Section 3.2 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 (Figure. 4c). Generally high accuracies in level adjustment using this approach have been reported by Pedersen et al. (2012). When participants were ready, they clicked a button on the screen to start the experimental scenarios. To keep participation sessions in reasonable lengths and avoid tediousness of repetitive tasks, each participant would only experience one experimental scenario, randomly selected from the four. Upon starting the scenario, the participant was located at the northwest corner of Piazza Vittoria in first person view. Instruction of movement control was given, followed by the assignment of Task 1.

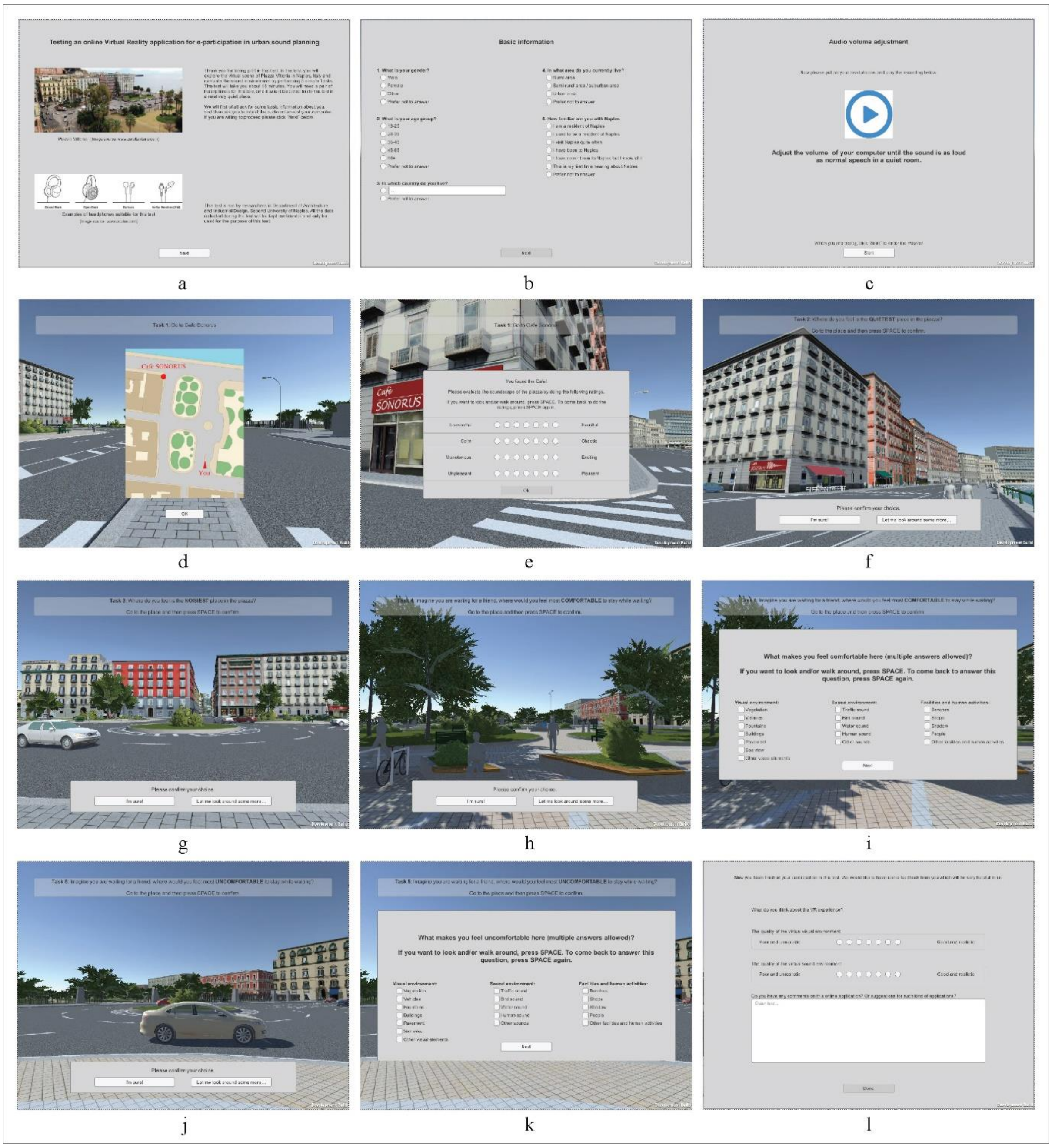

Figure. 4. Screenshots of the online survey interface. (Greyscale print)

Task 1 was to find Cafe SONORUS which was located at the southeast corner of Piazza Vittoria (Figure. 4d). This was to get the participant familiar with the virtual environment. When the participant found Cafe SONORUS, he/she was asked to evaluate the soundscape of the piazza by rating *uneventful-eventful*; *calm-chaotic*; *monotonous-exciting* and *unpleasant-pleasant* on 7-point scales. Eventfulness (or activity or variability) and pleasantness (or preference or affective impression) were found to be the two main dimensions that underlie soundscape perception (Axelsson et al., 2010; Berglund & Nilsson, 2006; Viollon & Lavandier, 2000), while calmness (or tranquillity) and excitingness (or vibrancy) are mixes of eventfulness and pleasantness in different directions (Axelsson et al., 2010; Cain et al., 2013). Ratings on these dimensions would reflect soundscape quality, and would be compared between the four scenarios to answer if shared-street design and traffic restriction improved the urban soundscape. The evaluation interface is shown in Figure. 4e.

Task 2 was to find where the participant thought to be the quietest place in the piazza (Figure. 4f) and Task 3 was to find the noisiest (Figure. 4g). After these, the participant was asked to imagine that he/she was waiting for a friend, and Task 4 was to choose a place where he/she would feel most comfortable to stay while waiting (Figure. 4h). When the participant arrived the place, he/she was asked to answer what made him/her feel comfortable there, by making multi-choice from a list of items in three categories: *visual environment (trees, vehicles, fountains, buildings, others); acoustic environment (traffic sound, bird sound, water sound, human sound, others); facilities/human activities (benches, shops, people, other)* (Figure. 4i). Task 5 was similar to Task 4. The participant was asked to choose a place where he/she would feel most uncomfortable to stay, and choose items that made him/her feel uncomfortable (Figure. 4j-k). Comparing location choices in Task 4 and 5 against those in Task 2 and 3, and item selections in the acoustic environment category against those in the other categories, would provide indications on the relevance of soundscape to human experience of the place in each scenario.

At the end of the participation session, participants were asked to rate the qualities of the visualisation and auralisation of the virtual environment on 7-point scales (*poor and* *unrealistic* to *good and realistic*), and leave comments that they had (Figure. 4l). Performance of their computers were captured in terms of frame rates during each task. All the participants' inputs, including their information, ratings, chosen locations and comments, were logged and maintained in an online database.

3.5. The online survey

The online survey was released in forms of a WebGL game and a Unity Web Player game. The Unity Web Player version provides higher visual and audio rendering qualities, but requires users to install a plug-in called Unity Web Player (size: 12 MB) beforehand. It was left to each participant to decide which version to use. English and Italian language options were also provided.

Invitations for the online survey were disseminated via online social media and emails. To attract Naples's local people, the invitations were published on Facebook page of Urbanistica Città Metropolitana Napoli and Facebook groups of local students. To attract people worldwide, the invitations were published on SONORUS's blog, ResearchGate page and Twitter account. Emailed individuals and groups including students and researchers in architectural and acoustical departments, practitioners in these two fields, as well as people outside these two fields in the researchers' personal networks.

4. Results

4.1. Overview of the responses.

106 completed responses to the online survey were received, of which 100 were valid. Figure 5 shows the statistics of the valid responses, including information of scenario, language,

gender, age, country, living area, familiarity with Naples, survey version, computer performance, and ratings of visualisation and auralisation qualities.

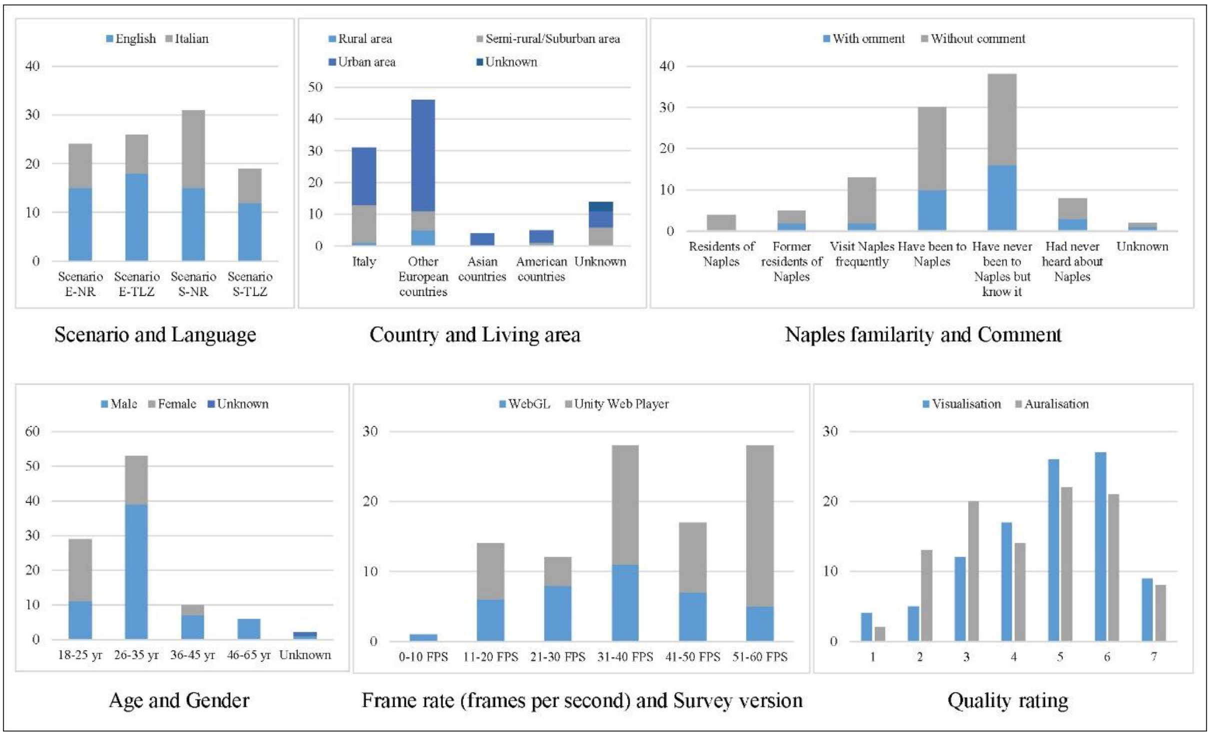

Figure 5. Overview statistics of the responses. (Greyscale print)

The four scenarios received unequal but generally balanced numbers of responses (Scenario E-NR: 24; Scenario E-TLZ: 26; Scenario S-NR: 31; Scenario S-TLZ: 19). Most participants opted for English language (English: 60%; Italian: 40%). Substantially more participants were from the younger generations (18-35 yrs: 82%; 36-65 yrs: 16%), and there were more males than females (Male: 64%; Female 35%) especially in the elder groups. One third of the participants lived in Italy while nearly half of the participants lived in other European countries. Most participants lived in urban areas (66%). Only a small part of the participants (22%) were familiar with Naples, i.e., being residents or former residents of Naples, or visiting Naples quite often. Higher interests in leaving comments were found in groups that were less familiar with Naples. Most participants (62%) were willing to install the plug-in to use Unity Web Player version for higher rendering qualities, and generally users of this version enjoyed higher frame rates during the participation sessions. Most participants rated the qualities of visualisation (79%) and auralisation (65%) as medium to high, i.e., with rating scores from 4 to 7.

The vast majority of the comments left by the participants were on the qualities of the visualisation and auralisation. Much fewer were on the survey design, such as not clear enough instruction on navigation and not enough options in Task 4 and Task 5. No one expressed any general opinions on subjects related to this study, such as street design or soundscape research.

4.2. Results of Task 1

Figure 6 plots percentages of participants by their soundscape ratings in Task 1. In Scenario E-NR, soundscape was rated to a slight extent as calm, monotonous and unpleasant. Even more neutral ratings were found in Scenario E-TLZ where calmness decreased a little while pleasantness increased a little. Ratings in the two shared-street scenarios have much clearer directions. In Scenario S-NR, soundscape was rated to a large extent as calm, monotonous and unpleasant, and to a slight extent as uneventful. In Scenario S-TLZ, pleasantness increased and soundscape was rated to a large extent as calm, monotonous and pleasant.

Four 2 × 2 between-subject ANOVAs were carried out to test the significance of the effects of street design and traffic restriction on the four dimensions of soundscape ratings. The results show that only effect of street design on the calm-chaotic rating ($df = 1, 96$, $F = 5.070$, $p = .027$, $\eta^2_p = .050$) and effect of traffic restriction on the unpleasant-pleasant rating ($df = 1, 96$, $F = 3.989$, $p = .049$, $\eta^2_p = .040$) were significant. The mean calm-chaotic rating decreased from -0.400 (S.D. = 1.525) in the existing-street scenarios to -1.000 (S.D. = 1.229) in the shared-street scenarios (-3 for calmest and 3 for most chaotic), and the mean unpleasant-pleasant rating increased from -0.364 (S.D. = 1.591) in the no-restrictions scenarios to 0.244 (S.D. = 1.510) in the TLZ scenarios (-3 for most unpleasant and 3 for most pleasant).

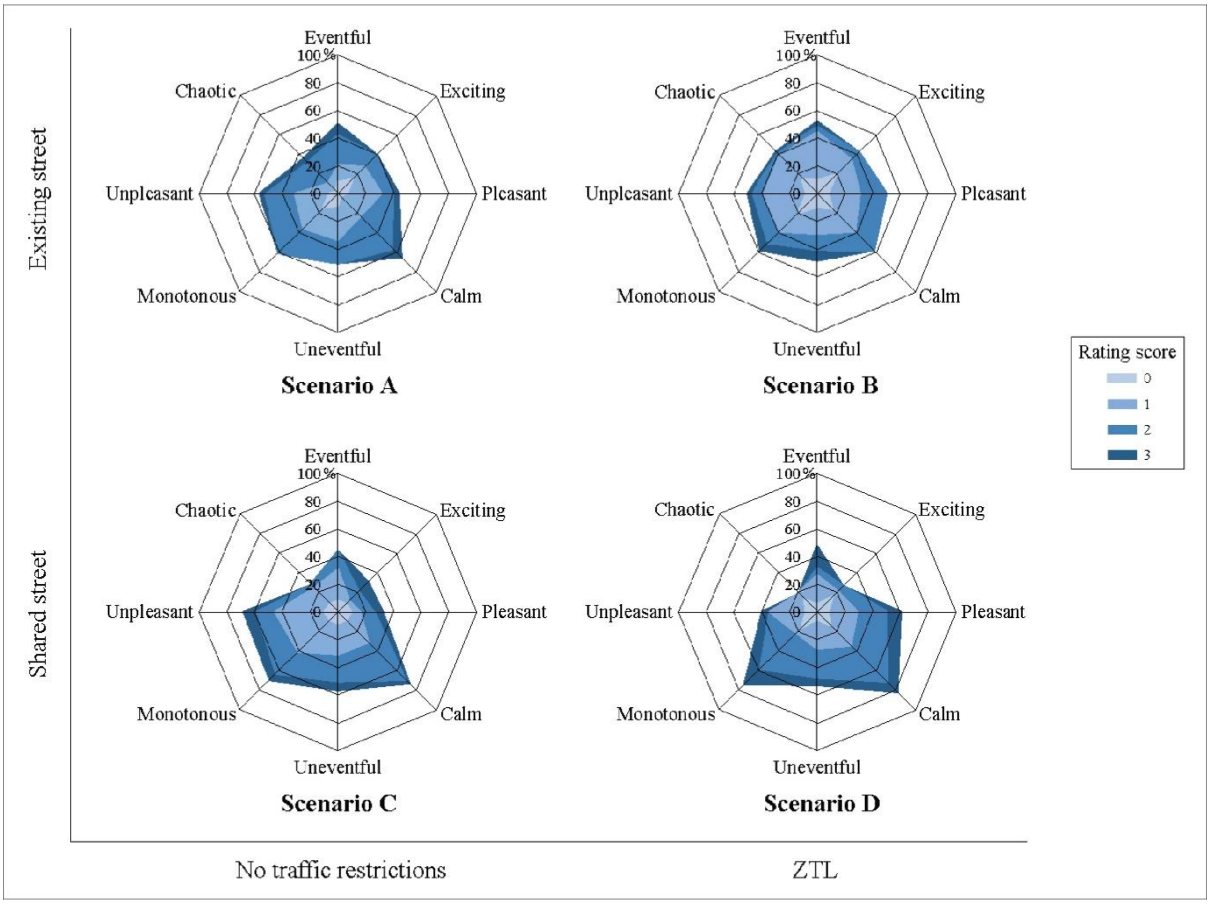

Figure 6. Soundscape evaluations of Piazza Vittoria in the four scenarios. (Greyscale print)

4.3. Results of Task 2 and Task 3

Figure 7 illustrates the locations of the quietest and noisiest places chosen by the participants in Task 2 and Task 3. For quietest places, participants tended to choose the central green areas in the no-restrictions scenarios, and the central green areas and the TLZ area in the TLZ scenarios. No noticeable differences were found between the existing-street and shared-street scenarios. For noisiest places, the locations were more dispersed and participants tended to choose the west part of the square where there were heavier traffic in all the four scenarios.

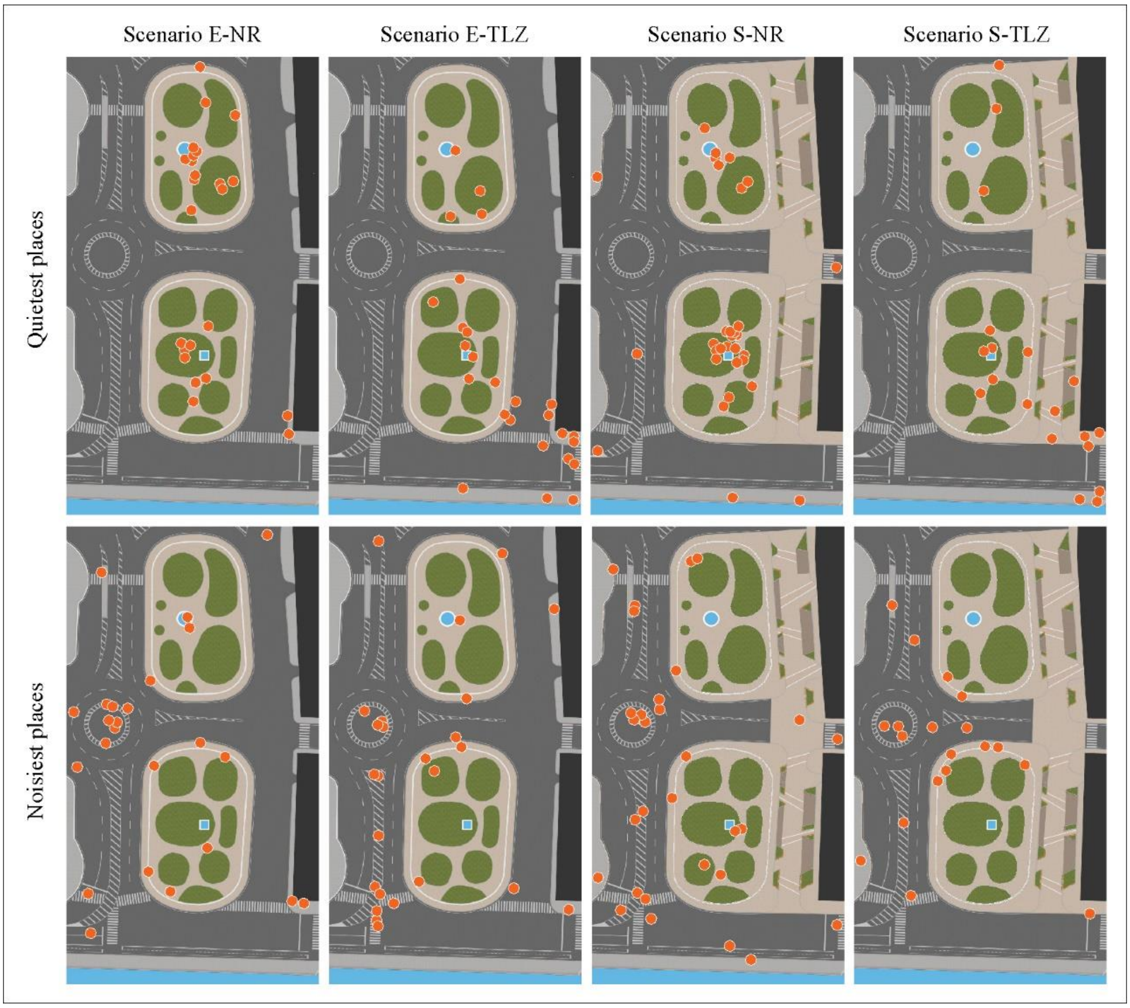

Figure 7. The quietest and noisiest places chosen by the participants in the four scenarios. (Greyscale print)

Comparing Figure 7 with traffic noise maps in Figure 3, high agreement can be found between participants' quietness/noisiness perception and the calculated level of traffic noise. However, it is also easy to spot out some very contrasting location choices. For example, for quietest places, three participants in Scenario S-NR chose locations right on noisy roads. For noisiest places, the contrasting location choices seem more explainable, since the chosen locations with low traffic noise levels were close to other sound sources such as restaurants, fountains and sea waves.

4.4. Results of Task 4 and Task 5

Figure 8 illustrates the locations of the most comfortable and uncomfortable places chosen by the participants in Task 4 and Task 5, and plots environmental elements by percentages of participants who selected them as influential on the location choices.

The place choices are similar to those of quietest and noisiest places. For most comfortable places, participants tended to choose the central green areas in the no-restrictions scenarios, and the central green areas and the TLZ area in the TLZ scenarios. Noticeably, participants in Scenario S-TLZ favoured locations close to the fountains more than those in Scenario E-TLZ did, despite the similar choices for quietest places and the same levels of traffic noise between these two scenarios. For most uncomfortable places, the locations were even more dispersed as compared to those of noisiest places. While there was still a general tendency to choose the west part of the square in Scenario S-TLZ, the tendency became less distinct from Scenario S-NR to Scenario E-TLZ, and became least distinct in Scenario E-NR.

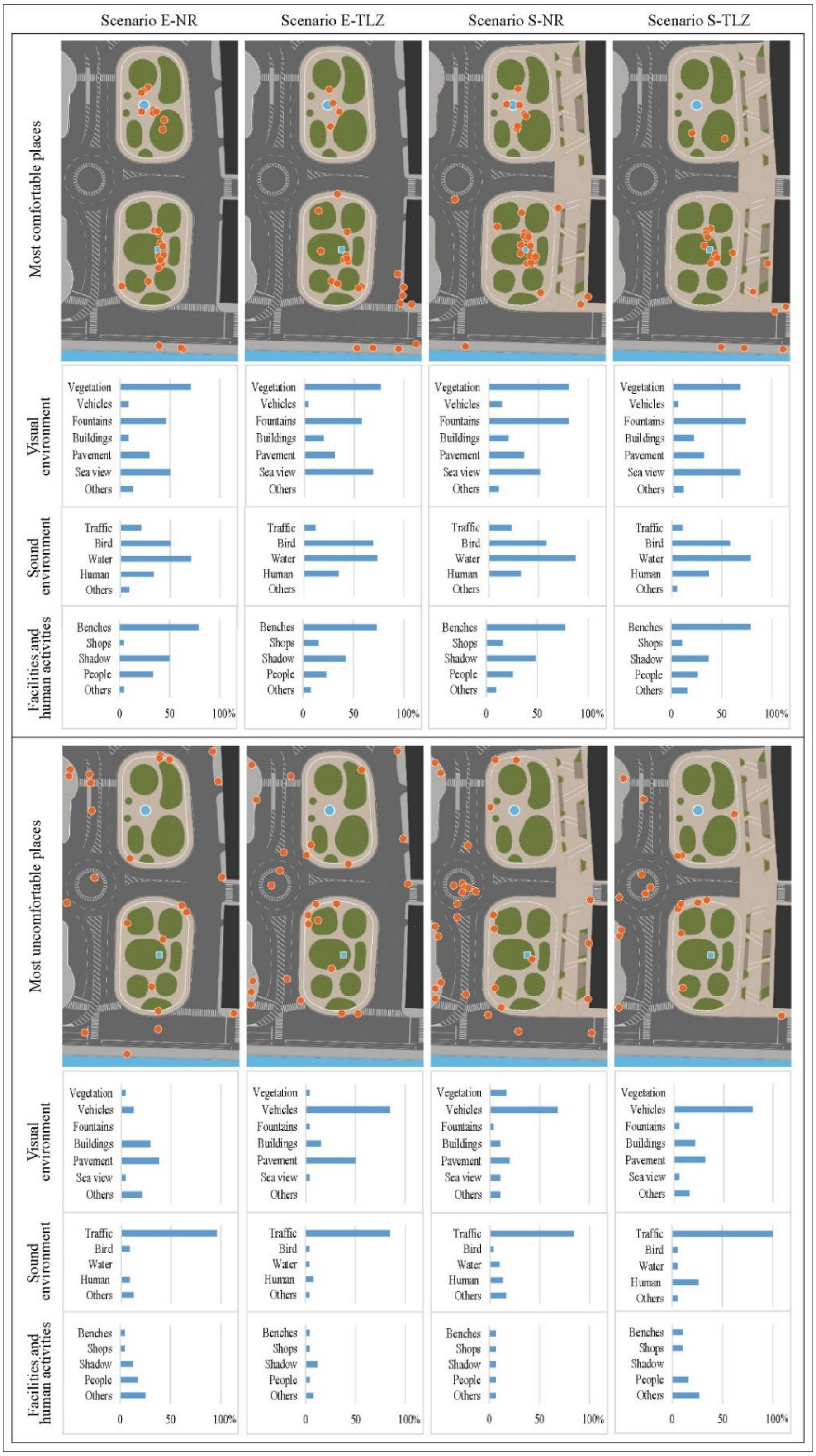

Figure 8. The most comfortable and uncomfortable places chosen by the participants in the four scenarios, and environmental elements that contributed to their choices. (Greyscale print)

Selections of influential environmental elements were generally similar across the four scenarios. For comfortable places, most participants liked vegetation, water sound and benches in all the four scenarios, as well as bird sound but with lower percentages. Fountains and sea view were also positive elements. Fountains were more contributing in the shared-street scenarios, while sea view was more contributing in the TLZ scenarios where there was less traffic at the waterfront. For uncomfortable places, vehicles and traffic sound were the dominant influential elements, although it is confusing that only a few participants chose vehicles in Scenario E-NR.

5. Discussion

5.1. Do shared-street design and traffic restriction improve urban soundscape?

Results of this study show some improvements in the urban soundscape by shared-street design and traffic restriction. Shared-street design tended to make the soundscape calmer, which might be explained partly by people’s general impression of higher safety of shared streets (Ruiz-Apilánez et al., 2017), and partly by increased naturalness of the particular shared street in this study which contributes to tranquillity (Pheasant et al., 2008). Traffic restriction increased the pleasantness of the soundscape, probably due to the decrease of traffic noise which is typically judged as unpleasant (Axelsson et al. 2010).

However, the improvements were not very strong in this study. The p values were above 0.01 and the mean rating differences were small for both improvements. There were also tendencies of other improvements or deteriorations as shown in Figure 6, but none of them were significant in the ANOVAs ($p > .05$). One possible reason for the weak effects might be the between-subject experimental design used in this study in which effects of experimental manipulation were likely to be less apparent than in within-subject design due to increased unsystematic variation. Another possible reason might be that shared-street design and TLZ were only applied on the east part of the case site in this study, while the soundscape that participants evaluated was of the entire site. Thus, it might be implied that shared-street design and/or traffic restriction can potentially improve urban soundscape more than the experimental results in this study have shown.

One possible improvement may arise from the potential interaction between shared-street design and traffic restriction as revealed in Figure 6. Comparing Scenario E-NR and Scenario S-NR in Figure 6, without traffic restrictions, soundscape pleasantness decreased in the shared-street scenario. While comparing Scenario E-TLZ and Scenario S-TLZ, with TLZ, soundscape pleasantness increased in the shared-street scenario. It might be explained by that, in shared-street scenarios, participants had higher expectations on the overall environmental quality, and thus were more sensitive or less tolerant to negative environmental elements such as traffic noise. Without traffic restrictions, traffic noise was prevalent, which might become a sharper nuisance in the shared-street scenarios and lead to lower soundscape pleasantness. While with TLZ, traffic noise was much less prevalent, and soundscape pleasantness increased in the shared-street scenarios as a result of the higher overall environmental quality.

In reality, shared-street design will almost always bring about changes in acoustic environment due to probable changes in traffic dynamics. If the changes in acoustic environment lead to lower traffic noise, then shared-street design itself might be enough to make the soundscape calmer and more pleasant. So knowledge on the causality chain of shared-street design, traffic dynamics and traffic noise would be very helpful for achieving higher improvements on soundscape by shared-street design. There is also indication for traffic restriction, that improvements on soundscape by traffic restriction might be more noticeable where the streetscape quality is higher, and in practice it might be reasonable to consider traffic restriction together with certain renovation of streetscape where necessary for higher improvements on soundscape.

5.2. How relevant is soundscape to human experience of the place in different street management scenarios?

The similarities between choices of the quietest/noisiest and the most comfortable/uncomfortable places, as well as the high influences of certain acoustic environmental elements on choices of the most comfortable/uncomfortable places, indicate high relevance of soundscape to human experience of the place. However, it is not to say that soundscape was determinative to human experience of the place. As shown in the selections of influential environmental elements in Figure 8, the visual elements vegetation, fountains and sea view, and the acoustical elements bird sound and water sound, were positive for human experience, and the visual element vehicles and the acoustical element traffic noise were negative for human experience. Vegetation and bird sound, fountains, sea view and water sound, as well as vehicles and traffic noise, were all closely bundled environmental elements. Thus the determinant of human experience could be the landscape, the soundscape, or the combination of them. Facilities such as benches could also play an important role in human experience. However, this is beyond the scope of this study, and benches were provided in appropriate locations all over the square in the virtual environment in this study, so they should have not overridden other environmental elements in influencing choices of places.

As for differences in the level of relevance of soundscape to human experience between different street management scenarios, results of this study do not show remarkable differences. One slight difference is that, for most comfortable places, participants in Scenario S-TLZ with shared street favoured fountains more than those in Scenario E-TLZ with existing street did. Comparison of selections of influential elements between these two scenarios suggests that this is probably because participants found fountains more visually attractive in Scenario S-TLZ. This tendency can also be found by comparing selections of influential elements for most comfortable places between Scenario E-NR and S-NR where a larger proportion of participants selected the visual element fountains in Scenario S-NR with shared street. The increased relevance of visual environmental elements in shared-street scenarios implies potentially decreased relevance of soundscape to human experience in these scenarios. Thus, while soundscape improvement would still be beneficial in such scenarios, marginal benefit to human experience might not be as high as in other scenarios. Such findings can help achieve more effective resource allocation in place making.

5.3. Limitations

To meet the requirements for online use, the auralisation used in this study was computationally cheap. Although it received acceptable quality ratings, it was not as satisfying as the visualisation, which might impair to some extent the validity of participants' soundscape perception. Possible improvements in auralisation quality might be made by introducing more sound sources with more variations, increasing the realism of synthesised sounds, and providing binaural technology with HRTF filtering and more accurate sound propagation. However, such improvements still remain very challenging today especially for online applications (Jiang et al., 2018).

Another limitation is lack of control on experimental conditions, since participants answered the surveys online using their own devices and at their own places. Apart from screen size and rendering quality which are also common issues in visualisation-based online surveys, the need to playback and evaluate audio content during the survey in this study introduced further uncertainties, for example, in headphone specifications, audio level calibration and quietness of the room. The added requirements in audio devices and calibration might also have increased the already high risk of participant selection bias that is typical in online survey. For example, in this study, there were substantially more participants in the 18 – 35 years age group, and much more males than females. Further discussion on these issues are needed for online surveys to be used with higher confidence for soundscape research.

6. Conclusions

This study aims to investigate if shared-street design and traffic restriction improve urban soundscape, and how relevant soundscape is to human experience of the place in different street management scenarios. With online virtual reality, a task-based online survey was carried out, and participants' responses to the 2 × 2 experimental scenarios, including existing street, shared street, no traffic restrictions and Traffic Limited Zone, were collected for analyses.

Results of this study show some improvements in urban soundscape by shared-street design and traffic restriction. Specifically, shared-street design made the soundscape calmer and traffic restriction made the soundscape more pleasant. There was also potential interaction between shared-street design and traffic restriction, that shared-street design might lead to lower soundscape pleasantness where traffic noise was prevalent without traffic restrictions, but increase soundscape pleasantness where traffic noise was less prevalent with traffic restrictions. Further studies on changes of traffic noise associated with shared-street designs themselves would be very helpful for achieving higher improvements on soundscape by shared-street design. There is also indication that improvements on soundscape by traffic restrictions might be more noticeable where the streetscape quality is higher.

High relevance of soundscape to human experience of the place is indicated in this study, although it is not sufficient to judge if the soundscape was determinative. A slight difference between different street management scenarios is that the relevance of the soundscape to the human experience might be lower in shared-street scenarios. So while soundscape improvement would still be beneficial to human experience in such scenarios, the marginal benefit might not be as high as in other scenarios.

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