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Relationships between landscape characteristics and the restorative quality of soundscapes in urban blue spaces

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Abstract

This study aims to explore the specific effects of audio-visual combinations on the restorative quality of soundscapes in blue spaces. In the experiments, 6 types of blue space were combined with 14 sounds, and the Short-version Revised Restoration scale (SRRS) was utilized by 65 volunteers to measure the restorative quality of the audio-visual combinations. On a scale from 1 to 9, the following results were obtained: (1) the water sound with the highest restorative quality is river sound (6.94), followed by fountain sound (6.59) and stream sound (6.41), and the sound of sea waves (5.85) has the lowest restorative quality; (2) in blue spaces with a high degree of urbanization (2.25), 9 types of sounds can improve restorative quality; (3) improving the visual quality of water, increasing the number of boats and reducing the number of paved areas can improve the restorative quality of audio-visual combinations; (4) it is appropriate to reduce plant diversity to improve the restorative effect in highly urbanized shore areas; and (5) footsteps are not appropriate in blue spaces with good natural surroundings. These results indicate that the restorative quality of soundscapes in blue spaces can be improved through landscape design, which provides implications for sustainable environment design.

Keywords: Blue spaces, Landscape characteristics, Restorative quality, Soundscape, Audio-visual combinations

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1. Introduction

Significant global health challenges, such as negative physical and psychological symptoms, are being confronted in the 21st century (Beaglehole et al., 2012; Danielsson et al., 2012). For example, COVID-19 has increased both disease mortality and mental health problems (Greenberg, 2020; Rajkumar, 2020), and psychological problems are difficult to eliminate in the short term (Brooks et al., 2020). These factors, combined with population growth, rapid urbanization and climate change, indicate that prevention approaches must be reconsidered (Das and Horton, 2012; Watts et al., 2015). With an increase in the urban population, the relationship between humans and nature is being increasingly considered during urban planning (Bush and Doyon, 2019; McEwan et al., 2020). Many studies have shown that short-term stays in natural environments can improve mental health (Beil and Hanes, 2013; Tyrväinen et al., 2014; M. P. White et al., 2013) and reduce stress (Hartig et al., 2003). Therefore, restorative environments are receiving an increasing amount of attention in urban environment research (Frumkin, 2001).

Restorative environments are typically natural environments with green and blue space (Labib et al., 2020; Mears et al., 2019; Voelker et al., 2016). A blue space is a natural or artificial outdoor environment that allows humans to access water either proximally (i.e., the person is either in, on or near the water) or remotely/virtually (i.e., the water can be seen, heard or otherwise perceived by the person) (Grellier et al., 2017). Similar to a green space, a blue space has the potential to serve as a healing landscape or public health resource (Gascon et al., 2017; Voelker and Kistemann, 2011). However, the effects of blue space on health depend on the type, quality and characteristics of the space (Voelker and Kistemann, 2011; Völker and Kistemann, 2015; M. White et al., 2010). Völker et al. explored the impact of walking distance and the frequency of blue spaces on physical and mental health and found that the frequent use of blue spaces can increase mental health (Völker et al., 2018). Bell et al. discovered that social interaction and psychological benefits are the most important benefits that people obtain from visiting blue spaces (de Bell et al., 2017). By comparing scenes with and without water, Whit et al. determined that the restorative quality of scenes with water was better (M. White et al., 2010), while in a study of coastal parks, Hipp et al. found that weather, air, water quality and other factors affect people's perceptions of restorative potential (Hipp and Ogunseitan, 2011). Studies have begun to explore the effects of restorative potential of blue space (Korpela et al., 2010; M. White et al., 2010), while the perception of the acoustic environment in blue space has been studied (Hong et al., 2020; Ren and Kang, 2015). However, specific influencing mechanisms of audio-visual interactions in the blue space should be evaluated further.

A soundscape is defined by the International Organization for Standardization (ISO) as "the acoustic environment as perceived or experienced and/or understood by a person or people, in context". Soundscape planning has emerged as a multidisciplinary school of thought that considers landscape, sound and experience (Prior, 2017). Similarly, soundscape design aims to blend sound, the audience and the environment to create a holistic landscape (Song et al., 2018). The information content of a sound also depends on the setting and context (Kang et al., 2016). Therefore, while information from the surrounding environment is primarily collected through sight (Smith, 1997), the role of sound should also be considered (Kang et al., 2016). The Perceived Restorativeness Soundscape Scale is a useful tool for research on restorative sounds (Payne, 2013). Ma et al. investigated the impact of city and park sounds on the quality of children's restoration and identified three characteristics of restorative sounds (Shu and Ma, 2018, 2020). Ratcliffe et al. conducted special research on the restorative quality of different bird songs and discovered that the restorative quality of bird songs is related to the associated environment (Ratcliffe et al., 2016). These studies proved that the soundscape is an important part of the restorative environment (Cerwen et al., 2016).

In recent years, increasing attention has been given to the study of audio-visual interactions in outdoor places (Li and Lau, 2020). Some researchers have found that audio-visual stimuli associated with nature have important effects on the restorative properties of urban green spaces (Deng et al., 2020) and suggested that design should extend beyond the dominant visual perspective and focus on the visitor experience from a multisensory perspective. Hong and Jeon developed a predictive model for audio-visual interaction and found that audio and visual information had effects of 24% and 76%, respectively, on overall satisfaction (Jeon and Jo, 2020). Research on the visibility of the sound source and the perception of sound has shown that the visibility of the sound source affects people's perception of sound, and with an increase in the volume of the sound, more attention, in terms of audio-visual processing, is focused on auditory stimuli (Haapakangas et al., 2020; Schäffer et al., 2019). In addition, Zhao et al. analysed the impact of landscape characteristics and soundscapes on the restorative quality of urban green space (Zhao et al., 2018). Specifically, research has shown that poor design is associated with psychological and physical discomfort (R. S. Ulrich, 1991). Well-designed blue spaces have multiple benefits on human health and well-being (Gascon et al., 2017; Voelker and Kistemann, 2011). Therefore, it is necessary to understand the key elements and characteristics of the visual landscape in blue spaces and their interaction with the soundscape. Previous studies have evaluated the pleasant and comforting effects of sounds (Alvarsson et al., 2010; Jeon et al., 2010; Wang and Zhao, 2019), with a focus on green spaces. Although the restorative effects of urban sounds have been explored (Jeon et al., 2021), restoration ranking of different water sounds in urban blue spaces is unclear. In addition, although the relationship between blue space and restorative perception has been investigated (Voelker and Kistemann, 2011; M. White et al., 2010), the impact of the characteristics of blue space landscapes on soundscape restorative quality has not been systematically explored. Therefore, to address these insufficiencies and to provide implications for urban sustainability, it is necessary to determine a reliable design basis for the restorative quality of urban blue spaces that considers both sight and sound.

This study aims to address the following questions: (1) What is the restorative effect of different sound sources in urban blue spaces? (2) Is the restorative effect of soundscapes different in blue spaces at different levels of urbanization? (3) Which landscape features in blue spaces affect the restorative quality of audio-visual combinations? (4) How can the effects of sound on restorative quality be improved in blue spaces? An internet experiment using audio-visual tests was conducted with 65 participants; the experiment involved 6 typical blue spaces and 14 typical sounds.

2. Methods

2.1. Audio and visual materials

Soundscapes are typically assessed via in situ experiences, audio-visual laboratory experiments, or narrative interviews (Aletta et al., 2016). In general, audio-visual experiments with controlled scenes, sounds and images are commonly employed (Li and Lau, 2020). However, in audio-visual experiments, it could be challenging to simultaneously investigate too many parameters (Alvarez et al., 2006). Therefore, the audio-visual perception of stimuli is usually categorized according to the parameters that were adjusted (e.g., audio-visual, audio-only, and visual-only).

2.1.1. Experimental images

Photographic images were utilized as substitutes for real visual landscapes. Although this method has some shortcomings, such as the poor effectiveness of photographic representations (Palmer and Hoffman, 2001), dependence on photographic equipment, and subjective bias (Yamashita, 2002), this method has been widely applied by previous researchers, and its reliability has been generally accepted (Arriaza et al., 2004; Hu et al., 2019; Wang et al., 2019).

According to previous studies, there are six types of urban blue spaces: oceans, rivers, streams, lakes, ponds and fountains (Voelker et al., 2016; Völker et al., 2018). To ensure the diversity of blue space types, the following blue spaces in different cities were selected as sample sites: Wellington, New Zealand; St Andrews, UK; Harbin, Liaocheng, Hohhot, Handan and Zhengzhou, China. A total of 969 images were taken approximately 1.55 m from the ground between 9 am and 4 pm (Wang and Zhao, 2019; Zhao et al., 2018). To reduce seasonal variations, all images were shot in the same season (i.e., summer) on sunny days to control lighting conditions and to avoid long focal lengths (Natori and Chenoweth, 2008). An OLYMPUS digital camera (SP-100EE) with a focal length of 35 mm was placed horizontally to capture the main features of the scene.

Based on the features identified in previous studies (Arriaza et al., 2004; Wang et al., 2016; Zhao et al., 2013), 19 major landscape characteristics were selected, as shown in Table 1. The representative images of each blue space type were selected from the images by 5 landscape architects, whose criteria included good photographic quality (e.g., clarity) and wide variation within each type (Y. Liu et al., 2019; Ren et al., 2018), according to the landscape characteristics (Table 1). Example images are shown in Fig. 1.

Table 1 Measurement of landscape characteristics.

Landscape characteristics	Abbreviation	Scores
Number of landscape elements	NLE	Only one = 0; two = 1; three = 2; four = 3
View scale	VS	Closed space = 0; slightly open space = 1; semi-open space = 2; open space = 3
Number of colours	NC	Only one = 0; two = 1; three = 2; four or more = 3
Colour contrast	CC	No contrast = 0; weak contrast = 1; clear contrast = 2; sharp contrast = 3
Percentage of land covered by vegetation	PLCV	No vegetation = 0; < 35% = 1; 36–70% = 2; 71–100% = 3
Type of land vegetation	TLV	No vegetation = 0; grasses or(and) shrubs = 1; only trees or tree with grass = 2; mixed vegetation = 3
Configuration of land vegetation	CLV	No vegetation = 0; orderly configuration = 1; semi-natural configuration = 2; natural configuration = 3
Growth status of vegetation	GSV	No vegetation = 0; bad = 1; moderate = 2; good = 3
Perceived diversity of vegetation	PDV	No vegetation or single = 0; low = 1; moderate = 2; high = 3
Percentage of land covered by water	PLCW	No water = 0; < 35% = 1; 36–70% = 2; 71–100% = 3
Visual naturalness of water	VNW	No water = 0; orderly form = 1; semi-natural form = 2; natural form = 3
Accessibility of water	AW	No water = 0; difficult to access = 1; neutral to access = 2; easy to access = 3
Quality of water	QW	No water = 0; bad = 1; moderate = 2; good = 3
Aquatic plants on water	APW	None = 0; a few = 1; more = 2; almost full cover = 3
Man-made elements	MME	None = 0; very little = 1; somewhat = 2; much = 3
Type of topography	TT	Almost flat = 0; slightly undulating = 1; much more undulating = 2, violently undulating = 3
Buildings	B	No building = 0; very little = 1; somewhat = 2; much = 3
Paved areas	PA	No paved path or square = 0; very little = 1; somewhat = 2; much = 3
Boats	S	No boat = 0; very little = 1; somewhat = 2; much = 3

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Fig. 1. Twelve images from the experiment: I-ocean, II-river, III-stream, IV-lake, V-pond, and VI-fountain; here, 1 and 2 are the serial numbers for blue space images of the same type.

2.1.2. Experimental sounds

The selection of sound was based on the results of a survey of urban blue spaces and a statistical study of common sound sources in cities (Hong and Jeon, 2015; J. Liu et al., 2013; M. Yang and Kang, 2013, 2016; W. Yang and Kang, 2005). While taking blue space images at different sample points, 320 urban blue space visitors were randomly interviewed, and were asked to choose the sounds they often heard in urban blue spaces. The survey results show that the sounds of streams, wind, leaves, birdsong, music, footsteps, voices, and traffic are the main sounds perceived in urban blue spaces (subjective perceptual frequency > 50%). Previous studies have shown that church bells, fountain sounds, sea waves, river sounds, insect sounds, and street machinery sounds are also frequently perceived in cities (J. Liu et al., 2013; M. Yang and Kang, 2016; W. Yang and Kang, 2005). Therefore, to ensure the coverage of urban sound sources, these 6 sounds were also selected for testing. A total of 14 typical sound sources were selected, similar to the case without sound (Table 2). In previous studies on the restorative effect of audio-visual environments, researchers usually considered few sounds (Deng et al., 2020; Zhao et al., 2018); thus, the restorative effect of urban sounds could not be fully understood. The 14 sounds in this study improve upon studies on sound source extensiveness and quantity.

A dual-channel sound recorder (ZODIAC/DIC10) was employed as a dual-channel audio capture device. The sound of road traffic was recorded 1 m from the road edge, 1.5 m from the ground, and > 3.5 m from any other reflective surface (Ren and Kang, 2015). The total traffic flow was 932 vehicles/h, where the flows of heavy vehicles, medium vehicles and light vehicles were 528/h, 264/h and 140/h, respectively. Furthermore, the average speed was 44.6 km/h, and the average speeds of heavy vehicles, medium vehicles and light vehicles were 32.6 km/h, 61.3 km/h and 40.0 km/h, respectively. Other sounds were recorded near the sound source; the distance from other reflection interfaces exceeded 3.5 m; and no other sound interference was detected (Ren and Kang, 2015; Ren et al., 2018). No rain or lightning was detected, and the wind speed was less than 5 m/s during the measurement period (Calleja et al., 2017).

Table 2 Abbreviations used to indicate different sound sources.

Sound source	Code	Sound source	Code
Bird song	BS	Church bells	CB
River sound	RS	Wind blowing	WB
Tree rustling	TR	Sea waves	SW
Insects sound	IS	Traffic sound	TS
Music	MS	Footsteps	FP
Fountain sound	FS	Adult voice	AV
Stream sound	SS	Street machinery sound	SM
No sound	NS		

All 14 sounds were adjusted to 50 dBA (Ren and Kang, 2015; Ren et al., 2018), as this research aims to evaluate sound type rather than sound level, and because the use of a consistent level ensures comparability (Hao et al., 2016; Hong and Jeon, 2013). In this study, the visual images were still scenes, and the audio signals consisted of a single dominant sound source that was easy to identify. Based on a previous study, each sound was edited to a duration of 20 s (Hong and Jeon, 2013; Ren et al., 2018). Adobe Premiere software was used to pair 14 sounds with 12 images (Wang and Zhao, 2019; Zhao et al., 2018), resulting in 168 (14×12) audio-visual combinations, which were randomly divided into 14 groups (a-n); no image or sound was utilized more than once in each group. The images in group 15 (o) were presented without sound.

2.2. Experimental design

2.2.1. Participants

In this experiment, the sample size was estimated based on the expected medium effect size, on alpha level = 0.5, and on statistical power = 0.8 using calculations provided by G*Power (Faul et al., 2009; Franz et al., 2007). The sample size estimation indicated that the study needed 30 participants. A total of 74 respondents completed the questionnaires, of whom 65 respondents (30 males and 35 females) between 16 and 44 years of age (M = 22.68, SD = 3.72), completed all surveys. Participants were asked to provide demographic information before completing the questionnaire. The questionnaires of participants who did not complete all questions or demographic information were considered invalid and removed from the sample.

2.2.2. Questionnaire

A questionnaire was used to collect data on the perceived restorative effect of the environment. Hartig's Perceived Restorativeness Scale (PRS) and the Revised Perceived Restorativeness Scale (RPRS) are applied to evaluate the restorative effects (Hartig et al., 1997), but they focus on recovery from mental fatigue (Han, 2003). The Short-version Revised Restoration Scale (SRRS) developed by Han(Han, 2003), which integrates the restorative environment theories of Kaplan (Kaplan and Kaplan, 1989) and Ulrich (Roger S. Ulrich, 1983), has a broader perspective and has proven to be a reliable and effective way to quantify the impact of the environment on the restorative effect. Therefore, the SRRS was used to assess the restorative potential of the environment. The SRRS consists of eight items that are spread equally across the four dimensions of emotion, cognition, physiology and behaviour (Table 3). Respondents use a 9-point Likert answer format to express their degree of agreement with the project, ranging from 1 (*completely disagree*) to 9 (*completely agree*). The inverse of the composite score of physiological response was calculated because it measures physiological arousal, which is the opposite of restorativeness (Zhao et al., 2018). The average score of each indicator was calculated. The mean of the eight indicators was employed as the restorative quality of an image or audio-visual combination (Wang et al., 2019; Zhao et al., 2018).

Table 3 SRRS (Imagine you are in the projected scene and score each item according to your perception, where 1 = totally disagree and 9 = totally agree).

		Scales
Emotional	Good natured	1___; 2___; 3___; 4___; 5___; 6___; 7___; 8___; 9___
	Relaxed	1___; 2___; 3___; 4___; 5___; 6___; 7___; 8___; 9___
Physiological	My breathing is becoming faster	1___; 2___; 3___; 4___; 5___; 6___; 7___; 8___; 9___
	My hands are sweating	1___; 2___; 3___; 4___; 5___; 6___; 7___; 8___; 9___
Cognitive	I am interested in the presented scene	1___; 2___; 3___; 4___; 5___; 6___; 7___; 8___; 9___
	I feel attentive to the presented scene	1___; 2___; 3___; 4___; 5___; 6___; 7___; 8___; 9___
Behaviour	I would like to visit here more often	1___; 2___; 3___; 4___; 5___; 6___; 7___; 8___; 9___
	I would like to stay here longer	1___; 2___; 3___; 4___; 5___; 6___; 7___; 8___; 9___

Ten associate professors of landscape architecture judged the 19 landscape characteristics of each image according to the scales in Table 1 (Wang and Zhao, 2019; Zhao et al., 2018). The interclass reliability of landscape characteristic scores across the panel was good (Cronbach's alpha ranged from 0.749 to 0.984), indicating that they could be used with confidence. Landis and Koch indicated that, if Cronbach's alpha > 0.801, then the interclass reliability was almost perfect, and if it ranged from 0.701-0.800, then it was good (Landis and Koch, 1977). Therefore, the average score of the panel was applied as the score for each image for a particular landscape characteristic.

2.3. Procedure

The effectiveness of internet surveys has been demonstrated in previous studies, and audio-visual survey data collected via the web are comparable to laboratory data (Lindquist et al., 2016; Roth, 2006; Wang et al., 2019). The online questionnaire was available between May 2020 and June 2020 via a web browser. The 12 images or audio-visual combinations were randomly presented in 15 groups. After viewing the image or the audio-visual combination, the participant was asked to provide a score according to the SRRS. All participants were asked to answer the online questionnaire using computers and headphones. Before answering the questions, participants were asked to maximize their browser window and use the sample audio to adjust their volume to a comfortable level (Lindquist et al., 2016). During this process, they could freely change their answer to any question before submitting it. Approximately 5 minutes on average was needed to complete the questionnaire. If participants rated all audio-visual combinations, then they were rewarded with a coupon. The overall process is shown in Fig. 2.

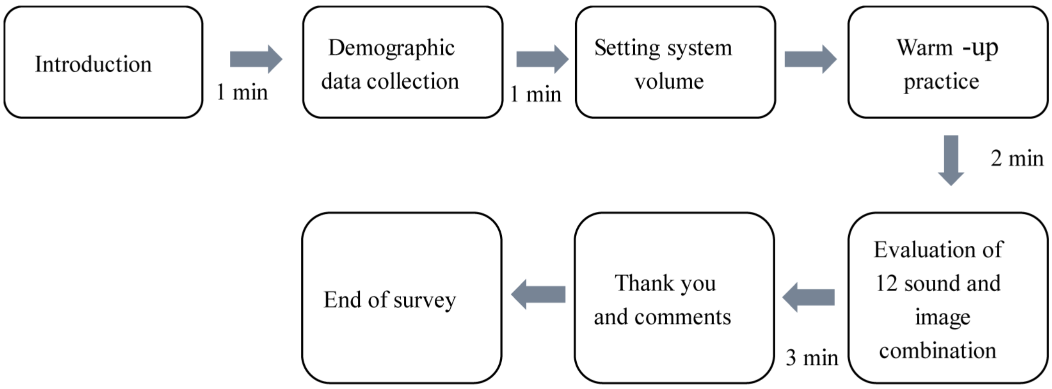

Fig. 2. Flow diagram of the online questionnaire.

Each subject evaluated audio-visual combinations in a random order to exclude any ordering effects, performing one test per day for three days (Jeon and Jo, 2020). We used the WJX.cn platform to enable the subjects to select answers in web. 10-s interval between each sound source (each combination was 20-s long). To relieve physical discomforts associated with prolonged screen use, we imposed a 30-min experimental time for each test, with sufficient rest time provided upon subject's requests (Jeon and Jo, 2020).

Based on the method suggested by Roth (Roth, 2006) to reduce dropout and the negative impact of dropout on online survey data, six measures were adopted (Table 4). The high-hurdle and warm-up techniques were applied, incentives were provided, no plugins were used, two-item-one-screen design was used, and the response time per page was recorded. Inclusion criteria was that participants had to exhibit attentiveness by not having an excessively long duration on the main survey questions (i.e. less than 30-s for each audio-visual combination)

(Lindquist et al., 2016).

Table 4. During an online survey, measures were taken to reduce dropout and the negative effects of dropout.

Measure	Description
High-hurdle technique	The demographic data (personalization) were collected before the evaluation of the stimuli
Warm-up technique	Personal data were collected and a test example was given before the real experiment started to ensure that the data collected in the experimental phase came from committed participants
Incentive	Participants were given the opportunity to enter a drawing for a gift certificate
No plug-ins	No plug-ins are needed, and the survey works with all modern web browsers.
Two-item-one-screen design	Each question is on a separate webpage. The results are saved to a database immediately after the submit button is clicked. If the participant drops out, all previous results and the point at which dropout occurred can be examined
Record of response time per page	The response time is recorded for each webpage/rating. Data quality issues due to an interruption to the experiment can be identified

2.4. Statistical analysis

In the experiment, twelve images were reassembled for the same sound. Data analysis was carried out using SPSS 25.0. First, data were assessed for normality based on the absolute values for skewness (<2.0) and kurtosis (<4.0) (West et al., 1995). No substantive departure from normality was found in the data. The interclass reliability of restorative scores was tested, and one-way analysis of variance (ANOVA) was conducted to explore the significance of the effects of each sound on the restorative quality of the visual landscape. In addition, HCA was employed to classify the 12 images for further comparison. Since the same team participated in all 15 different experimental environments, a repeated measure analysis of variance (RM ANOVA) was performed to study the effects of images and audio-visual information on restoration. Stepwise multiple linear regression analysis was performed to explore the driving force of landscape characteristics on restorative quality and the effects of soundscapes on restorative quality.

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3. Results and discussion

Before processing the data, the interclass reliabilities of the restorative scores of the a-o groups were calculated to verify the reliability of the data. Cronbach's alpha ranged from 0.738 to 0.957. In general, the results indicated the internal reliability of restorative quality for all groups. According to independent-sample t-tests, gender did not significantly affect the restorative perception of the 15 groups. Therefore, to study the relationship between landscape characteristics and the restorative quality of soundscapes, the results were divided into four parts.

3.1. Restorative effects of different sound sources

The mean and standard deviation of the restorative quality of all audio-visual combinations and the images presented without sound are shown in Fig. 3(a). According to the average score, 7 of the 14 sounds (birdsong, river sounds, tree rustling, insect sounds, music, fountain sounds, and stream sounds) had higher restorative quality than landscapes without sound, and the other 7 sounds scored lower than the landscapes without sound. The one-way ANOVA showed significant differences in restorative quality among the 15 groups ($F = 43.613$; $p < 0.001$), which means that soundscape was a nonnegligible factor affecting restorative quality in blue spaces. However, the pairwise comparisons showed that the restorative scores of images with birdsong ($p < 0.001$), river sounds ($p < 0.001$), tree rustling ($p = 0.017$), insect sounds ($p = 0.020$), music ($p = 0.024$), and fountain sounds ($p = 0.036$) were significantly higher than the scores of images with no sound; the scores of images with sea waves ($p = 0.006$), traffic sounds ($p = 0.001$), footsteps ($p < 0.001$), adult voices ($p < 0.001$), and street machinery sounds ($p < 0.001$) were significantly lower than the scores of images with no sound; and stream sounds, church bells, and wind had no significant influence.

Previous studies have shown that natural sounds promote mental restoration more than man-made sounds (Cerwen et al., 2016; Zhang et al., 2017). When hearing natural sounds, listeners may become aware of the existence of life-giving environmental elements. This study shows that the restorative quality of natural sounds (such as wind blowing and sea waves) is not better than that of environments without sound, possibly because the message conveyed by the sound changes people's moods (Kang et al., 2016). For example, although the sea waves is a natural sound, it may be associated with high tide and tsunamis. Therefore, the sea waves was found to have a lower restorative quality than no sound at all, as shown in Fig. 3(a). The restorative effect of birds singing in blue spaces was the highest of the sounds analysed, consistent with previous results (Ratcliffe et al., 2013; Zhao et al., 2018). This result suggests that birdsong triggers feelings of connection with the natural environment and natural activities (Ratcliffe et al., 2016).

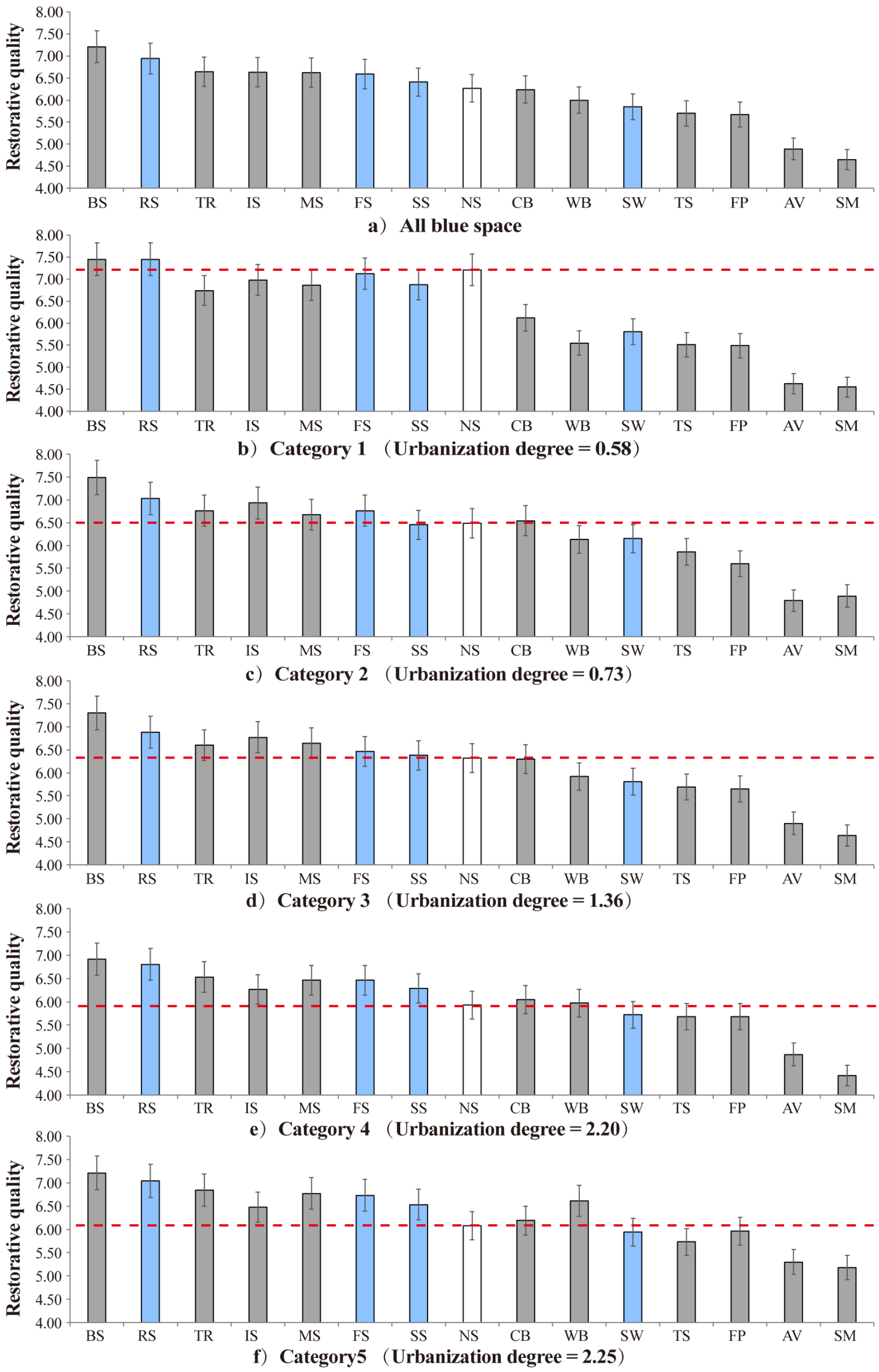

Fig. 3. Mean restoration scores (± standard error) of sounds under different conditions: a) All blue spaces, b) Category 1, c) Category 2, d) Category 3, e) Category 4, and f) Category 5. Columns in blue indicate that the sound of water was present, while the red dotted lines indicate the restoration scores when no sound was present.

Interestingly, a comparison of the restorative quality of all water sounds (blue column) and the case without sound (white column) in Fig. 3(a) revealed found that river sounds, fountain sounds and stream sounds could improve the restorative quality of blue spaces, with river sounds having the highest restorative quality, followed by fountain sounds and stream

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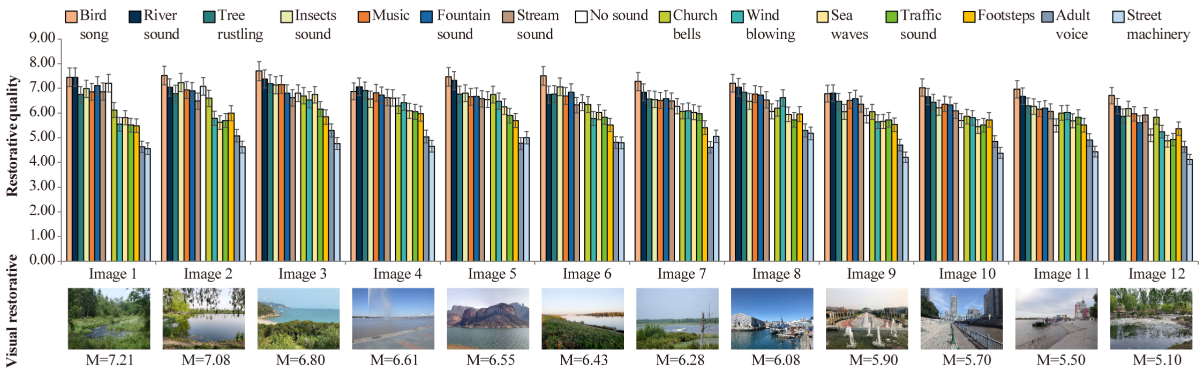
sounds, and sea waves having the lowest restorative quality. Therefore, not all water sounds have a high restorative quality, possibly due to the different acoustic parameters of different water sounds (Patón et al., 2020).



Landscape characteristics

	Image 1	Image 2	Image 3	Image 4	Image 5	Image 6	Image 7	Image 8	Image 9	Image 10	Image 11	Image 12
NLE	1.50	2.00	2.60	2.10	1.70	1.70	2.30	1.60	2.60	2.60	2.40	2.50
VS	0.80	2.10	2.60	3.00	2.50	3.00	2.60	1.70	2.70	2.10	2.30	1.70
NC	1.90	2.20	2.60	2.20	1.90	2.00	2.50	2.60	3.00	2.40	2.80	2.30
CC	1.10	1.40	1.50	0.80	1.50	1.50	1.30	1.40	2.20	0.90	1.10	1.20
PLCV	3.00	1.80	2.20	0.70	1.20	2.30	2.20	0.00	1.00	0.90	0.70	1.60
TLV	3.00	2.90	2.80	1.30	0.70	1.20	3.00	0.00	1.60	1.70	1.30	2.50
CLV	3.00	1.70	2.90	1.50	2.30	2.60	2.90	0.00	1.00	0.90	1.10	1.50
GSV	3.00	2.40	2.70	1.40	1.20	2.10	2.50	0.00	1.90	2.00	1.50	2.10
PDV	2.90	2.10	2.00	0.90	0.70	1.30	2.10	0.00	0.80	0.60	0.40	1.80
PLCW	1.00	2.30	1.90	2.80	2.30	1.80	2.20	2.20	1.20	1.40	2.00	2.00
VNW	3.00	2.00	2.90	1.60	3.00	2.60	2.80	1.40	1.00	1.00	1.40	1.70
AW	2.30	2.50	2.50	2.10	2.30	2.30	2.20	2.20	2.70	1.70	2.90	2.70
QW	2.90	2.20	2.70	2.20	2.50	2.40	2.50	2.20	2.10	1.30	1.60	1.10
APW	1.70	1.10	0.80	0.40	0.60	1.00	1.30	0.40	0.20	0.30	0.40	1.20
MME	0.10	1.50	1.60	2.30	0.00	0.60	1.00	2.80	3.00	3.00	3.00	2.30
TT	0.40	0.60	1.90	0.10	2.90	1.10	0.30	0.30	1.40	0.80	0.70	0.70
B	0.00	0.30	1.40	1.10	0.00	0.60	0.10	2.60	2.90	2.80	2.20	0.50
PA	0.00	0.80	0.40	2.10	0.00	0.30	0.10	1.40	3.00	2.80	2.50	1.70
S	0.00	0.00	1.00	0.40	0.00	0.00	0.90	2.50	0.00	0.00	1.70	0.00

Fig. 4. Mean restoration scores (± standard error) for 12 images with or without sound and the scores of the landscape characteristics for each image.

The 12 images were arranged from high to low in terms of the restorative score of the images in the case without sound (Fig. 4). The order of the images, average restoration score of each image, quality of the audio-visual combinations, and landscape characteristics of the images are shown in Fig. 4. Some audio-visual combinations that do not match, such as addition of the sound of ocean waves to a river scene were deliberately considered. This was done to have sufficient contrast, helping participants make up their mind regarding what they like or dislike (Van Renterghem et al., 2020). The different effects of sounds suggested that sound features played an important role in promoting restorative qualities of environments. This is possibly explained by the degree of matching between a sound triggering the imagination of particular environments and the landscapes shown by a photograph. The ranking of sound restorative quality was found to change among pictures with different landscape characteristics. For example, in the picture with the highest visual restoration score (Image 1), only birdsong and river sounds had a higher rehabilitation quality than the case without sound. However, in the pictures with the lowest visual restoration score (Image 12), the restorative quality of sea waves, traffic sounds, adult voices, and street machinery had lower restorative quality than that of pictures shown without sound. Thus, the characteristics of the landscape affect both the visual restorative quality and the restorative quality of the soundscape. Therefore, it is necessary to further explore the impact of landscape characteristics on the restorative quality of soundscapes.

3.2. Effects of the urbanization degree of blue space on soundscape restorative quality

Hierarchical clustering analysis (HCA) can reliably identify clusters in data according to the similarity between samples (Lee and Yang, 2020). HCA has been applied in soundscape and audio-visual studies (Ge and Hokao, 2005; Jia et al., 2020; Y. Liu et al., 2019). To improve the efficiency of the work and explore the restorative quality of 14 sounds in different blue spaces based on the evaluation results of experts, 19 landscape characteristics were clustered into 4 groups of characteristics based on the average Euclidean distance and the between-group linkage (Fig. 5a).

Since the HCA method was used, the four landscape feature categories were not compatible or overlapping. In general, four landscape feature categories represent naturalness of the blue space; the degree of visual contrast of blue space elements; openness of the blue space; and urbanization degree of the blue space. Similarly, according to the experts' ratings of the 19 landscape features of the images, 12 images were divided into five categories of blue spaces with the HAC method (Fig. 5b).

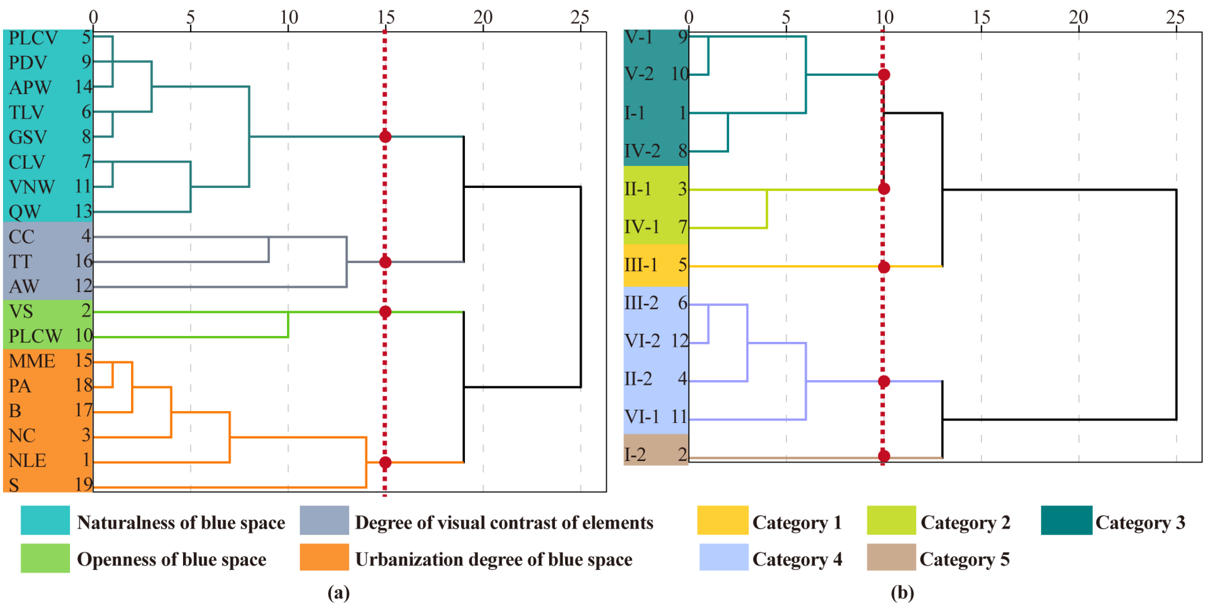


Fig. 5. HCA of the landscape characteristics and the 12 images. (a) Tree diagram of 19 landscape features. The cut-off point is selected to determine the 4 clusters. (b) Tree diagram of 12 images. According to the scores of the landscape features, the 12 images can be divided into 5 categories.

The characteristics of five spatial category images are shown in Fig. 6. Category 1 has the highest degree of nature and lowest degree of urbanization. Category 2 has the highest degree of openness and a relatively low degree of urbanization. Category 3 has moderate degrees of nature and urbanization. Category 4 has a relatively high degree of urbanization and a relatively low degree of nature. Category 5 has the highest degree of urbanization and lowest degree of nature. According to the classification of the abovementioned images, the blue space images of different urbanization degrees were grouped, which was helpful to further investigate the rehabilitation effect of sound in different categories of blue spaces.

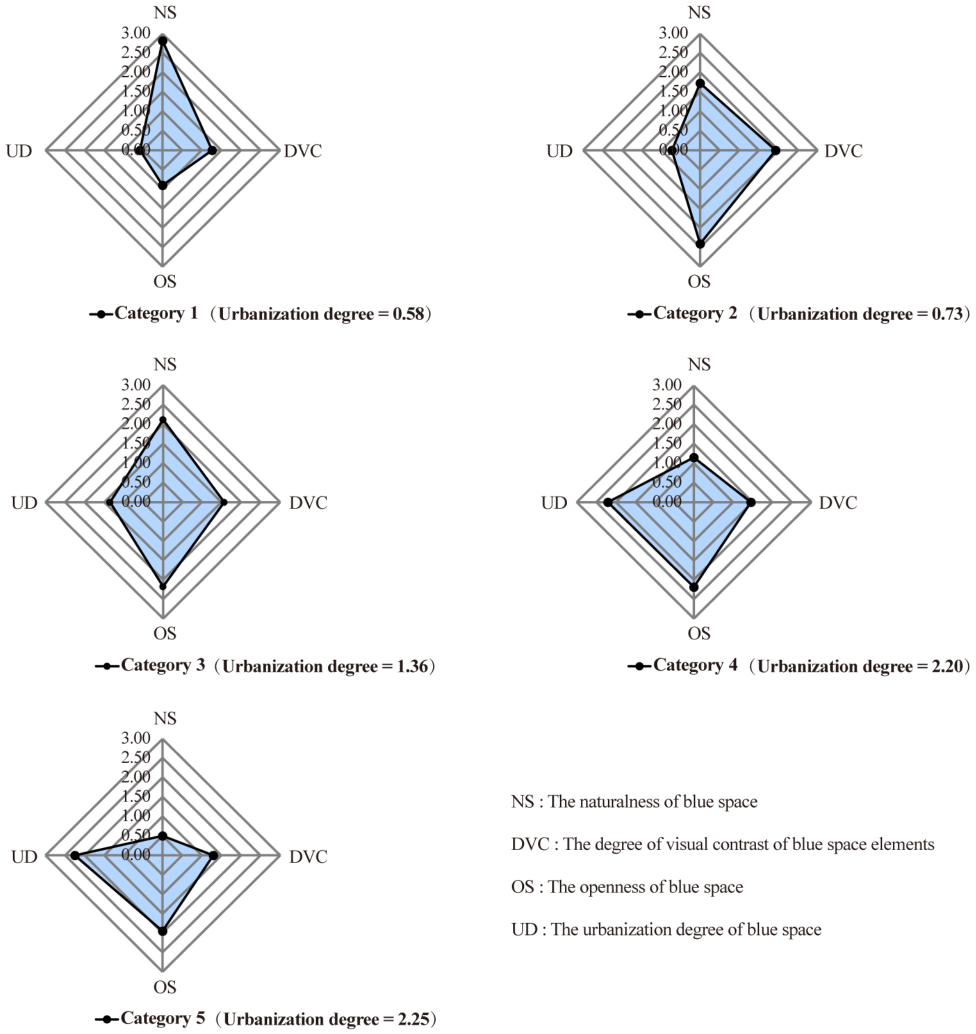


Fig. 6. Average score of 4 indicators for each type of blue space.

Fig. 3(b-f) shows descriptive data of sounds in blue spaces with different degrees of urbanization. As the data for the different sound conditions were derived from a group of respondents using the same scale, a series of RM ANOVAs were used to compare the significance of the differences in the restorative qualities of different sounds for the same type of space. Each type of space was tested separately. When Mauchly's test indicated a violation of sphericity, the Greenhouse-Geisser correction was applied, and the corresponding p-values were reported (Haapakangas et al., 2020; Simkin et al., 2020). The results of Greenhouse-Geisser calibration showed that the differences in the restorative capacities of different sounds were statistically significant for five spatial types: Category 1 [F (7.287, 466.344) = 44.628, $p < 0.001$, $\eta^2 = 0.411$]; Category 2 [F (9.632, 1242.565) = 53.891, $p < 0.001$, $\eta^2 = 0.295$]; Category 3 [F (9.885, 2560.180) = 109.395, $p < 0.001$, $\eta^2 = 0.297$]; Category 4 [F (9.886, 2560.383) = 101.289, $p < 0.001$, $\eta^2 = 0.281$]; and Category 5 [F (8.024, 513.511) = 18.536, $p < 0.001$, $\eta^2 = 0.225$].

In general, the restorative quality of birdsong was the highest among the five spatial categories, followed by river sounds, while mechanical sounds and adult voices were the two lowest spatial categories. Interestingly, compared with the restorative quality of an environment without sound (red dotted line in Fig. 3), many of the sound sources had a good restorative effect in blue spaces with a high degree of urbanization. When a blue space has a low degree of urbanization (0.58), there are two types of sound with higher restorative quality than the environment without sound (Fig. 3b). When a degree of urbanization is moderate (1.36), there are seven types of sound with higher restorative quality than that environment without sound (Fig. 3d). When a blue space has a high urbanization degree (2.25), there are 9 types of sound with higher restorative quality than an environment without sound (Fig. 3f). Thus, while the restorative effect of sound is not obvious in natural blue spaces, it is necessary to improve the restorative quality of the environment through sounds for blue spaces with higher degrees of urbanization, possibly because the degree of urbanization of a blue space will affect the restorative quality of the soundscape (Hu et al., 2019). Therefore, it is necessary to consider the restorative effect of soundscapes according to the degree of urbanization of a blue space. This result could have an important role in sustainable urban planning.

Note that compared with an environment with no sound (red dotted line in Fig. 3), environments with water sounds had more obvious restorative effects in blue spaces with high urban attributes (from Category 1 to Category 5 in Fig. 3). Thus, in urban blue spaces, the restorative quality of the environment can be improved by playing water sounds.

3.3. Effects of landscape characteristics on audio-visual combination restorative quality

To determine the quantitative relationship between the soundscape restorative quality and landscape characteristics, stepwise multiple regression was performed. The landscape characteristics were employed as independent variables, and the restorative quality of the audio-visual combinations was selected as a dependent variable. The important predictors selected by stepwise multiple linear regression are shown in Table 5.

The normality of residuals followed a normal distribution (the Z value from the Kolmogorov–Smirnov test ranged from 0.096 to 0.238, $p > 0.05$). The variance analysis results indicated a linear correlation between the landscape characteristics and the restorative quality ($p < 0.05$). The collinearity statistics show that the values of tolerance are greater than 0.2 and that the range of the variance inflation factor (VIF) is less than 10, which indicates that collinearity bias was avoided(Arriaza et al., 2004). Therefore, all models can be accepted.

Many studies have shown that a natural environment can relieve mental stress better than a man-made environment (Chawla et al., 2014; Hajrasouliha, 2017; Morita et al., 2007). The results of this stud indicated that the type of water is an important predictor of the restorative quality of different sounds (river sounds, tree rustling, fountain sounds, music, church bells, stream sounds, sea waves, and no sound) in a blue space (Table 5). In particular, the type of water can explain approximately 84.8% of the variance in the restorative quality of stream sounds ($p < 0.001$). This result probably occurs as people are more attracted to water when they are in blue spaces, which causes the type of water to become an important indicator that people use to judge the restorative quality of a blue space.

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Table 5 Significant predictors of restorative quality when no sound or soundscape is present. B and β indicate unstandardized regression coefficients of indicators and standardized regression coefficients of indicators, respectively.

Sound	Factors	B	β	t	Sig.
NS (R^2 = 0.745; adjusted R^2 = 0.720)	(constant)	4.115		10.019	0.000
	Quality of water	1.008	0.863	5.412	0.000
BS (R^2 = 0.673; adjusted R^2 = 0.641)	(constant)	7.508		85.814	0.000
	Paved areas	-0.239	-0.821	-4.540	0.001
RS (R^2 = 0.745; adjusted R^2 = 0.719)	(constant)	5.786		26.257	0.000
	Quality of water	0.540	0.863	5.403	0.000
TR (R^2 = 0.636; adjusted R^2 = 0.600)	(constant)	5.578		21.391	0.000
	Quality of water	0.494	0.797	4.180	0.002
IS (R^2 = 0.631; adjusted R^2 = 0.594)	(constant)	6.986		61.109	0.000
	Paved areas	-0.284	-0.794	-4.135	0.002
MS (R^2 = 0.673; adjusted R^2 = 0.640)	(constant)	5.548		22.860	0.000
	Quality of water	0.499	0.820	4.532	0.001
FS (R^2 = 0.780; adjusted R^2 = 0.758)	(constant)	5.233		22.271	0.000
	Quality of water	0.634	0.883	5.953	0.000
SS (R^2 = 0.848; adjusted R^2 = 0.833)	(constant)	5.428		39.997	0.000
	Quality of water	0.460	0.921	7.475	0.000
CB (R^2 = 0.423; adjusted R^2 = 0.365)	(constant)	5.447		18.162	0.000
	Quality of water	0.368	0.650	2.705	0.022
WB (R^2 = 0.349; adjusted R^2 = 0.284)	(constant)	5.830		45.000	0.000
	Boats	0.312	0.591	2.316	0.043
SW (R^2 = 0.624; adjusted R^2 = 0.586)	(constant)	4.424		12.259	0.000
	Quality of water	0.666	0.790	4.070	0.002
SM (R^2 = 0.399; adjusted R^2 = 0.339)	(constant)	4.878		41.292	0.000
	Paved areas	-0.183	-0.632	-2.576	0.028

NS: No sound; BS: Bird song; RS: River sound; TR: Tree rustling; IS: Insects sound; MS: Music; FS: Fountain sound; SS: Stream sound; CB: Church bells; WB: Wind blowing; SW: Sea waves; SM: Street machinery sound.

As shown in Table 5, boats are a predictor of the restorative quality of wind (p = 0.043). When the number of boats increases, the restorative quality of wind improves, possibly as places with a large number of boats mostly included docks or ports, and people want to hear the wind in those places due to psychological expectations (Jo and Jeon, 2020). The study also revealed that paved areas had a negative effect on the restorative quality of birdsong, insect sounds and mechanical sounds (standardized beta < 0) (Table 5). Thus, the restorative quality of birdsong, insect and street machinery sounds decreases when the paved area of a blue space increases. In a blue space with birdsong, insect or street machinery sounds, the paved area can be reduced to improve the restorative effect of the audio-visual environment.

3.4. Effects of sound on restorative quality

The effect of sound on restorative quality was defined as the change in the quality of restoration capacity that occurs when a sound is introduced into a previously soundless landscape. In this study, the effects of 14 sounds on restorative capacity were calculated using the following formula(Wang and Zhao, 2019; Zhao et al., 2018):

$$S_{ij} = N_{ij} - N_i \quad (1)$$

where S_{ij} is the effect of the j_{th} sound on the restorative capacity of the i_{th} image; N_{ij} is the restorative capacity of the i_{th} image with the j_{th} sound; and N_i is the restorative capacity of the i_{th} image without sound.

To further compare the effects of the 14 sounds on the restorative quality of different images, the restorative quality of the sounds was calculated according to the abovementioned formula for different images. Fig. 7 shows the effects of sound on the restorative quality of 12 images compared to the case without sound.

In general, compared to the case without sound, birdsong improved the restorative quality of all the images, while the adult voice and street machinery reduced the restorative quality of all the images. Compared with the case without sound, except for image 2, river sounds improved the restorative quality of the other images. The restorative quality of different water sounds also differed, and compared to river, fountain and stream sounds, sea waves improved the restorative quality of only one image (image 11), which indicated that different water sounds have different effects on the restorative quality of a blue space and that the restorative quality of sea waves in a blue space is usually lower than that of no sound. Interestingly, the restorative quality of traffic sounds is higher than that of the environment without sound in image 11 (Fig. 7), possibly because image 11 was a primarily artificial environment, and people adapted to traffic sounds. In addition, as all sounds in the experiment were played at 50 dBA, which is not an unbearable level, the restorative effect of traffic sounds was good.

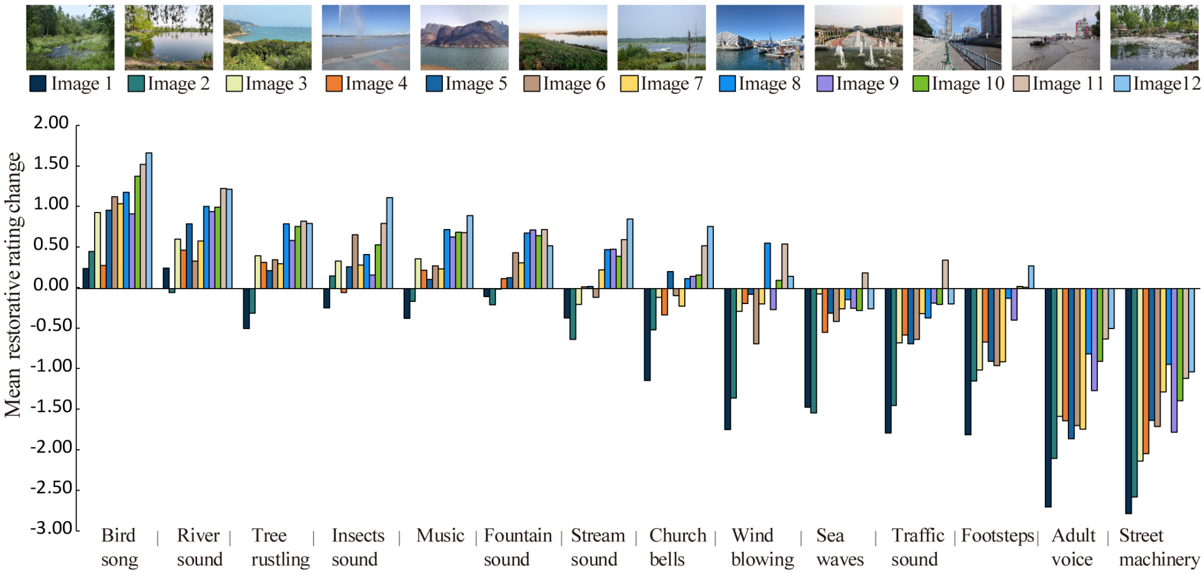

Fig. 7. Change in the average restorative quality of different audio-visual combinations.

As shown in Fig. 7, different sounds have different effects on the restorative quality of a landscape. Accordingly, it can be said that the restorative quality of one sound is better than that of another. However, the restorative effects of sound are also influenced by the visual characteristics of a landscape. If sound is introduced at the wrong place, even sound with high restorative quality is not as good as the case of no sound. For example, although river sounds generally improved the restorative quality of an urban blue space, its restorative effects were lower than those of the case without sound for image 2 (Fig. 7). Conversely, if a sound with an average restorative quality lower than that of no sound is played in the correct place (such as the previous example of traffic sounds), the restorative quality can be improved. Therefore, the effects of sound on restorative quality should be considered in environments with different landscape characteristics (such as the presence of water and man-made elements).

To determine the quantitative relationship between the effect of sound on restorative quality and landscape characteristics, stepwise multiple regression analyses were conducted. The landscape characteristics were used as independent variables, and the effects of sound on restorative quality were used as the dependent variable. The important predictors selected by stepwise multiple linear regression are shown in Table 6. The results of the variance analysis revealed a linear correlation between the landscape characteristics and the effects of sound on restorative quality. The collinearity statistics show that the values of tolerance are greater than 0.2 and that the range of VIF is less than 10, which indicates that collinearity bias was avoided(Arriaza et al., 2004). Therefore, all models can be accepted.

Table 6 Important predictors of the effects of 14 sounds on restorative quality.

Effects of sound on restorative quality	Adjusted R^2	Factors	Standardized Beta	T	Sig.	Tolerance	VIF
Bird song	0.441	Quality of water	-0.702	-3.114	0.011	1.000	1.000
River sound	0.394	Quality of water	-0.670	-2.857	0.017	1.000	1.000
Tree rustling	0.494	Man-made elements	0.735	3.429	0.006	1.000	1.000
Insects sound	0.497	Quality of water	-0.736	-3.443	0.006	1.000	1.000
Music	0.568	Man-made elements	0.779	3.935	0.003	1.000	1.000
Fountain sound	0.486	Buildings	0.730	3.378	0.007	1.000	1.000
Stream sound	0.481	Quality of water	-0.727	-3.345	0.007	1.000	1.000
Church bells	0.512	Quality of water	-0.746	-3.538	0.005	1.000	1.000
Wind blowing	0.580	Perceived diversity of vegetation	-0.786	-4.021	0.002	1.000	1.000
Sea waves	0.349	Perceived diversity of vegetation	-0.639	-2.629	0.025	1.000	1.000
Traffic sound	0.394	Man-made elements	0.670	2.853	0.017	1.000	1.000
Footsteps	0.884	Quality of water	-0.729	-6.452	0.000	0.825	1.213
		Perceived diversity of vegetation	-0.378	-3.340	0.009	0.825	1.213
Adult voice	0.653	Quality of water	-0.827	-4.657	0.001	1.000	1.000
Street machinery sound	0.355	Perceived diversity of vegetation	-0.643	-2.654	0.024	1.000	1.000

The quality of water was a reliable predictor of the effects of 6 sounds on restorative quality. As shown in Table 6, the quality of the water had a negative effect on the effects of birdsong (p = 0.011), river sounds (p = 0.017), insect sounds (p = 0.006), stream sounds (p = 0.007), church bells (p = 0.005), and adult voices (p = 0.001). In places with poor water quality, these sounds had a stronger effect on restorative quality.

Man-made elements were a predictor of the effects of 3 sounds. As shown in Table 6, man-made elements had a positive effect on the effects of tree rustling (p = 0.006), music (p = 0.003) and traffic sounds (p = 0.017). In other words, in a blue space with more man-made elements, restorative effects of tree rustling, music and traffic sounds could be more obvious. The effect of fountain sounds on restorative quality was influenced by the number of buildings (p = 0.007) (Table 6). In other words, in a blue space with increased number of buildings, restorative effects of fountain sounds could be more obvious.

The perceived diversity of vegetation could predict the effects of 3 sounds on restorative quality. As shown in Table 6, the perceived diversity of vegetation had a negative effect on the effects of wind (p = 0.002), sea waves (p = 0.025) and street machinery (p = 0.024). Thus, in a blue space with less diverse vegetation, restorative effects of wind blowing, sea waves and mechanical sounds could be more obvious.

As shown in Table 6, in the model for the effects of footsteps on restorative quality, both the quality of water (p < 0.001) and perceived diversity of vegetation (p = 0.009) had statistically significant negative effects, and the model accounted for 88.4% of the variance in the data. In a blue space with better water quality and higher vegetation diversity, footsteps will reduce the environmental restorative quality. Therefore, in a blue space with better water quality and higher vegetation diversity, paving materials that avoid footsteps should be utilized.

In general, the stepwise multiple linear regression analysis results showed that changing specific landscape characteristics can modulate the impact of sound on restorative quality. Therefore, the impact of landscape characteristics on sound restorative potential should be considered in soundscape planning. To increase the restorative capacity of urban blue space, it is indispensable to focus on the properties of visual landscapes. First, setting up a waterscape in blue space and enhancing its accessibility can improve its restorative potential by building a hydrophilic plat-form, constructing some infrastructures to encourage the activities linked to water. Second, for soundscape designs that are aimed at improving the restorative potential of urban blue spaces, understanding their association with vision is necessary. Some sounds can be introduced to a landscape by creating some elements to produce an appropriate sound, such as creating habitats and nests to attract birds or building fountains. Alternatively, proper visual landscapes should be created based on the sound of the specific blue space.

In practical soundscape design, there are two design strategies: (1) eliminate or reduce unwanted sounds and (2) introduce desired sounds into the appropriate environment (Kang et al., 2016). However, identifying desired or unwanted sounds also relies on the visual landscape (Wang and Zhao, 2019). Understanding the connection between sound and sight is a prerequisite for the design of soundscapes in blue spaces. Therefore, the restorative quality of a blue space can be improved by producing the desired sound. For example, according to the results of this study, in areas with poor visual water quality, an environment that is suitable for bird and insect activity can be created, and a flowing waterscape can be established to introduce

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these sounds, such as placing fountains in locations with many buildings, planting trees that are prone to rustling (e.g., poplar or bamboo) or playing music in blue spaces with a large number of man-made elements. In addition, the rehabilitation effect of soundscapes can be improved by controlling landscape characteristics, for example, introduce wind, sea wave sounds in blue spaces with low vegetation diversity to increase restorative qualities and by using paving materials that avoid footsteps in blue spaces with better water quality and higher vegetation diversity. These results provide new knowledge for sustainable environmental design.

4. Conclusions

This study investigated the relationship between landscape characteristics and soundscape restorative quality in blue spaces. The main conclusions can be summarized as follows:

1) The average restorative quality of different sounds in a blue space varies greatly (ranging from 7.21 to 4.65). Regarding water sounds, river sounds have the best restorative quality, followed by fountain sounds, stream sounds, and sea waves. Furthermore, the restorative qualities of these sounds are not constant, as they depend on the type of blue space.

2) The degree of urbanization of a blue space may affect the change in soundscape restorative quality. It is worth noting that compared to green spaces, blue spaces often have more unique solutions for meeting higher construction requirements of waterfronts. For instance, landscape elements of blue spaces are often comprehensively considered from the perspective of aesthetics and structural engineering to play the dual role of waterfront protection and hydrophilic activities. We found that, compared to blue spaces with a low degree of urbanization, blue spaces with a high degree of urbanization require more sounds to improve restorative qualities. Therefore, some sounds can be introduced in blue spaces by creating waterfront structures that produce sounds with high restorative qualities.

3). The quality of water is an important factor that affects the audio-visual combination restorative quality of a blue space, and the restorative effect of the audio-visual environment can be improved by improving the visual quality of water (such as by improving the transparency of water). In a blue space where birdsong, insect sounds and street mechanical sounds often occur, the paved area should be reduced to improve the restorative quality of the sound. The restorative quality can be improved by increasing the number of boats in windy blue spaces (such as docks and ports).

4). Changing some landscape characteristics can modulate the effects of sound on restorative quality. Introduce wind, sea waves sounds in blue spaces where with low vegetation diversity to increase restorative quality. In blue spaces with good water quality and high vegetation diversity, pavement that amplifies footsteps should not be installed.

These results are expected to help urban planners, managers and landscape architects design blue spaces with high restorative quality and promote environmental sustainability. However, in real environments, multiple sounds usually occur simultaneously, producing complex interactions. This study focused on the impact of a single sound on the restorative quality of a landscape, so the impact of composite sounds on restorative quality should be considered in future studies.

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