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Impacts of sights and sounds on anxiety relief in the high-density city

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HIGHLIGHTS

- Impacts of environmental sounds and sights on anxiety were examined.
- Environmental sounds and sights significantly and interactively affected anxiety.
- Impact of sounds on anxiety was 4.67 times greater than that of sights.
- People are more sensitive to sounds in natural scenes than in artificial scenes.
- Fully natural sounds are most effective in relieving anxiety than other sounds.

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ABSTRACT

Anxiety is one of the most common mental health disorders in the world. Although acoustic and visual environments are known to influence many other aspects of mental health, we know little about their independent and interactive effects on the levels of anxiety of high-density city dwellers. We conducted a laboratory experiment using a two-way factorial design (four visual environments × five acoustic environments) and randomly assigned participants to 20 treatment conditions. Before exposure to a condition, they engaged in the Trier Social Stress Test to induce a moderate level of anxiety. A total of 223 urban dwellers reported their anxiety level before and after a randomly assigned environmental treatment. The results showed that acoustic and visual environments had significantly interactive influence on anxiety relief. The impact of acoustic environments on anxiety relief was 4.67 times greater than the impact of visual environments. Environments with more natural features, regardless of whether they were acoustic or visual, played a greater role in reducing anxiety than environments with more artificial features. The combination of green scenes and fully natural sounds gave a significantly greater anxiety relief than any other acoustic-visual environments. The implications of these results for planning and design in high-density cities are discussed.

1. Introduction

1.1. *Anxiety—one of major challenges of mental health in urban areas*

An estimated 970 million people worldwide are suffering from mental health problems (Dattani et al., 2021). Among them, an estimated 284 million people are suffering from anxiety disorder, estimated at around 4 percent of the global population (Dattani et al., 2021). In recent years, anxiety has become an even more severe public health crisis in the world (Brunier & Drysdale, 2022). As a mental state, anxiety includes feelings of apprehension, tension, nervousness, and worry, accompanied by physiological and hormonal arousal (Spielberger, 2010). A large body of empirical studies reports that anxiety can impair human health through multiple pathways and can lead to severe mental and physical illness, which can then lead to more anxiety, creating a vicious cycle (Wheatley, 1997). Moreover, individuals who suffer from

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anxiety are at a greater risk of suicide (Hocaoglu, 2015).

Due to social, economic, and environmental factors, anxiety is more prevalent in urban than rural areas (Srivastava, 2009). Comparing to rural areas, urban areas suffer more from air pollution, traffic noise, a lack of green space, and high population and building density, which can potentially contribute to a higher level anxiety of urban residents (Pelgrims et al., 2021). These environmental problems are highly intense or severe in high-density cities thus they may contribute to a high prevalence of anxiety disorder (Chan et al., 2021; Gruebner et al., 2017; Lederbogen et al., 2011; Mouratidis, 2019). Identifying the specific features of the high-density urban environment that may affect the anxiety levels of city dwellers is therefore important. Based on a review of theoretical and empirical studies, we suggest that studies of impacts of high-density urban environments on anxiety should consider both acoustic and visual characteristics.

1.2. Existing evidence of impacts of acoustic-visual environments on anxiety

The effects of visual environments are typically the focus of studies in this area, as extensive information about an environment can be readily acquired through observation (Ulrich, 1981). Visual contact with nature or natural elements has been repeatedly demonstrated to relieve anxiety (Wang et al., 2022; Yin et al., 2020), while urban environments that lack vegetation typically increase anxiety levels (Jiang et al., 2019; Ulrich, 1986).

The acoustic environment has also been proven to have profound effects on anxiety. For example, artificial noise soundscapes are consistently reported to trigger anxiety and are unlikely to be restorative (Zhou et al., 2020). The different acoustic information from a street at night can also arouse or reduce pedestrians' anxiety (Ohno & Matsuda, 2013). Unlike mechanical sounds, natural sounds can effectively reduce anxiety (Zhang et al., 2023) and stress (Grahn & Stigsdotter, 2010; Hedblom, Gunnarsson, Iravani, et al., 2019) and promote a positive mood (Annerstedt et al., 2013; Benfield et al., 2014), while exposure to traffic noise can cause anxiety and depression and even increase stress hormone levels, thereby triggering inflammatory and oxidative stress (Hahad et al., 2019).

One study also reveals a small positive interactive effect between natural visual and acoustic environments on anxiety reduction in a healthcare setting. After introducing natural sounds and large images of natural landscapes into a waiting room in a student health centre, a small change was reported in terms of anxiety reduction (Watts et al., 2016). Another study shows that pedestrians on a street at night can associate acoustic information with various possible scenarios, which can arouse or reduce anxiety (Ohno & Matsuda, 2013). Although few studies examine the combined effects of acoustic and visual environments on anxiety, significant positive interactive effects on mental states have been frequently reported, such as mental restoration (Zhao, Xu, et al., 2018), stress recovery (Park et al., 2020), enhanced perceived happiness (Hong & Jeon, 2013, 2014), an enhanced sense of tranquillity (Watts et al., 2016), and promoted postive moods (Jiang et al., 2021).

In summary, research into the impacts of acoustic and/or visual environments on anxiety is increasing. However, a significant knowledge gap remains, which should be addressed by new studies.

1.3. The critical knowledge gap

Both visual and acoustic environments have been found to have specific influences on anxiety levels, but their combined effects remain unknown. Particularly in contemporary high-density cities, a wide variety of environmental sounds mix and are also combined with various types of visual environments. Mixed acoustic-visual environments are ubiquitous but vary greatly in high-density cities, due to the mixed land uses and human activities. The combination of acoustic and visual environments can sometimes be jarring. For example, a natural view may be accompanied by intense artificial noises from nearby roads or buildings. However, the extent of the effects of complex mixtures of acoustic and visual environments on anxiety states, compared with single acoustic or visual stimuli, remains largely unknown.

1.4. Research objectives and questions

To address this knowledge gap, we conducted an experimental study in a virtual reality lab. The experiment was aimed at measuring the restorative effects on anxiety of 20 pairs of acoustic-visual environments (four acoustic environments $\times$ five visual environments). The ranking analysis aims to provide evidence on planning and design strategies that suitable for different conditions of sites in high-density cities. Further comparing each of 19 acoustic-visual environments with the control group (no visual & no sound), we aim to find specific combination of acoustic and visual environments were adverse or favourable. Specifically, we addressed three main research questions.

1. To what extent do acoustic and visual environments independently and interactively influence participants' anxiety?
2. To what extent do the selected five types of acoustic environments and the four types of visual environments influence anxiety?
3. What is the rank order of the effects of the resulting 20 acoustic-visual environments on anxiety?

2. Methods

We conducted a laboratory experiment using a two-way factorial design (four visual environments and five acoustic environments). We randomly assigned 240 participants to one of 20 acoustic-visual environments (conditions) within a virtual reality lab. Through a questionnaire survey, we measured changes in anxiety before and after they watched video clips. We describe our methods in the five sections below: participants, acoustic and visual stimuli materials, measures of changes in anxiety, procedure, and statistical analysis.

2.1. Participants

We recruited 240 healthy adult residents from Hong Kong as participants. Our study received ethical approval from a university (kept anonymous). The participants were recruited through the universities' bulk email system and via flyers posted in various public spaces both on and off campus. We asked whether they had diagnosed sight or hearing problems or mental illnesses in last month, those who answered yes were not eligible to participate. The participants were randomly assigned to groups and each group was assigned to one of 20 videos. The groups each consisted of approximately six female and six male participants (Appendix A). After removing statistical outliers (Mean $\pm$ 3 Standard deviation was used as outlier filters), data samples from 109 men (48.9 %) and 114 women (51.1 %) were obtained for statistical analysis. The majority of the participants were younger than 25 years (78.9 %) or in early middle age (between 26 and 30 years: 14.3 %), while mean age was 22.9 (SD = 4.8). All were Hong Kong residents and most originated from either the Hong Kong SAR., at 53.4 %, or from mainland China, at 35.0 %. Most of the participants were raised in cities, with 47.5 % in highly dense cities and 29.1 % in dense cities. The descriptive statistics of the participants' socio-economic and demographic characteristics are presented in Table 1.

2.2. Materials of acoustic and visual stimuli

A total of 20 videos were produced with various pairs of acoustic-visual environments (Fig. 1). These included three 10-minute videos of typical urban settings (park, plaza, and street) and five environments representative of Hong Kong (Fig. 2). These were selected as they also represent generic examples of high-density urban environments. We did

Table 1
Descriptive statistics of participants' socio-economic and demographic characteristics.

Measures	Number	Percent (%)	Measures	Number	Percent (%)
Gender			**Marital Status**		
Male	109	48.9	Never married	210	94.2
Female	114	51.1	Married or living with a partner	13	5.8
Age			**Density of Living Place**		
18–25	176	78.9	High density city	149	66.8
26–30	32	14.3	Dense city	51	22.9
31–40	11	4.9	Low density city	14	6.3
41–50	4	1.8	Suburban area	6	2.7
Above 50	0	0	Rural area	3	1.3
Nationality			**Education**		
Hong Kong SAR, China	119	53.4	High school	75	33.6
Mainland China	78	35.0	Bachelor	95	42.6
Other regions in East Asia	5	2.2	Master	47	21.1
South Asia	12	5.4	Doctorate	6	2.7
North America	5	2.2	**Income (HK$)**		
Europe	3	1.3	<5,000	18	8.1
South America	1	0.4	5,001–10,000	41	18.4
Density of birthplace			10,001–20,000	81	36.3
Highly dense city	106	47.5	20,001–30,000	35	15.7
Dense city	65	29.1	30,001–50,000	30	13.5
Low dense city	36	16.1	>50,000	18	8.1
Suburban area	10	4.5			
Rural area	6	2.7			

Note: 100 HK$ = 12.7 US$ = 12.8 EUR (08/28/2022).

not select scenes with specific local (e.g., temples, sculptures, significant local landmarks) or unusual characteristics (e.g., luxury cars, pets, people with special appearances). We used a 4 K high-resolution camera (Sony ILCE-7RM2 4 K camera, 35 mm full frame CMOS image sensor) with a tripod to record the videos at roughly human eye level (about 160 cm above the ground). No large trees, tall buildings, or other visual barriers within 10 m of the camera's view were filmed to avoid significant visual obstacles. All the videos were recorded between 10 a.m. and 4p.m. on slightly cloudy or sunny days to reduce any variability in lighting conditions. We captured 20 min of video footage at each site. Three landscape researchers selected a two-minute continuous sample for each site, based on the criteria that it should be highly representative of the type of space (park, plaza, street), of high quality, and contain no disturbances or abrupt activities. Thus, we ensured the scenes had typical pedestrian and traffic flow; that they did not contain unusual or traditional architecture or landscape features, or visually attractive or off-putting animals, vehicles, or people; and that no objects were obscuring the view from the camera lens. By combining samples from five sites for each of the treatment conditions, we created 10-minute videos for each type of acoustic-visual environment. We also created a "no scene" condition, which showed only a neutral, grey screen, with no other visual content. This was included as a control condition for visual perception.

We aimed to ensure that the acoustic environments we created were common in high-density cities and we attempted to minimise the impact of cultural and historical characteristics. After conducting site investigation, we selected three sound sources: traffic, ventilation, and natural sounds. Traffic is frequently heard in many areas of high-density cities, due to the prevalence of motor vehicles in urban environments (Brown et al., 2011; Raimbault & Dubois, 2005). Ventilation sounds signify the anthropocentric noises that can often be heard in high-density cities. They are typically generated by air conditioners and exhaust fans in restaurants. Natural sounds are also common in urban green spaces. To ensure that our findings were generalisable, we chose artificial and natural sounds that are familiar to most people living in cities, regardless of their geographical location. We did not include any unique or rare sound stimuli that were produced by unusual sites, birds, animals, or

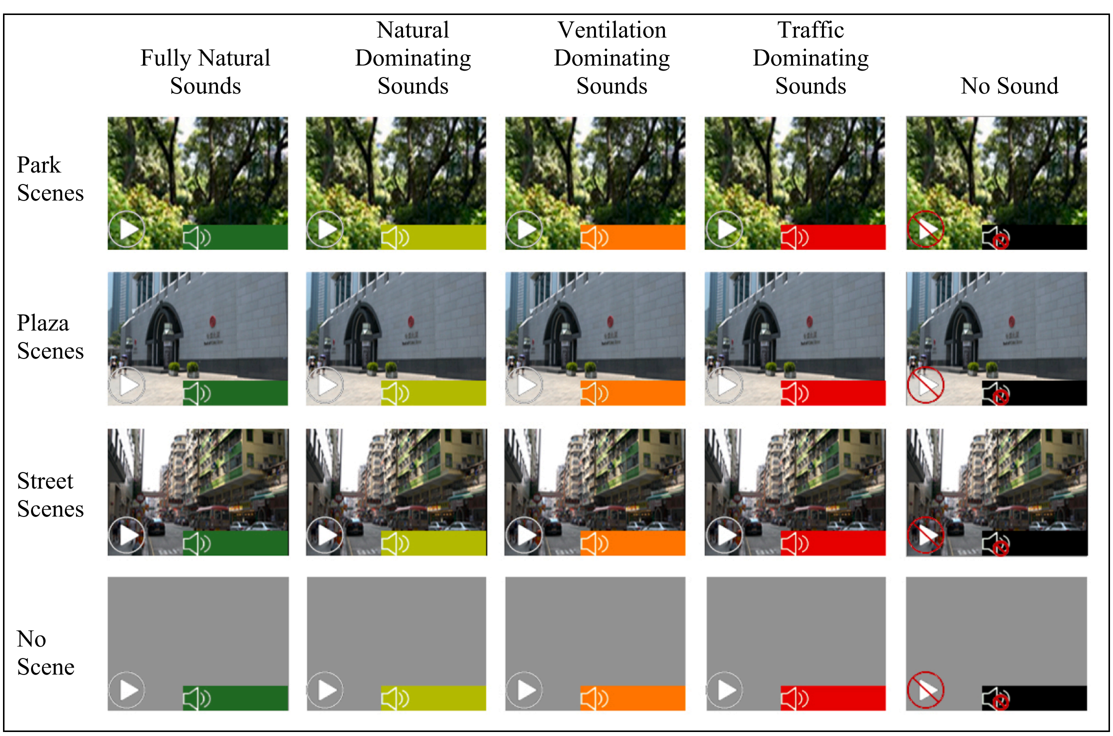

Fig. 1. The twenty combinations of acoustic and visual environments.

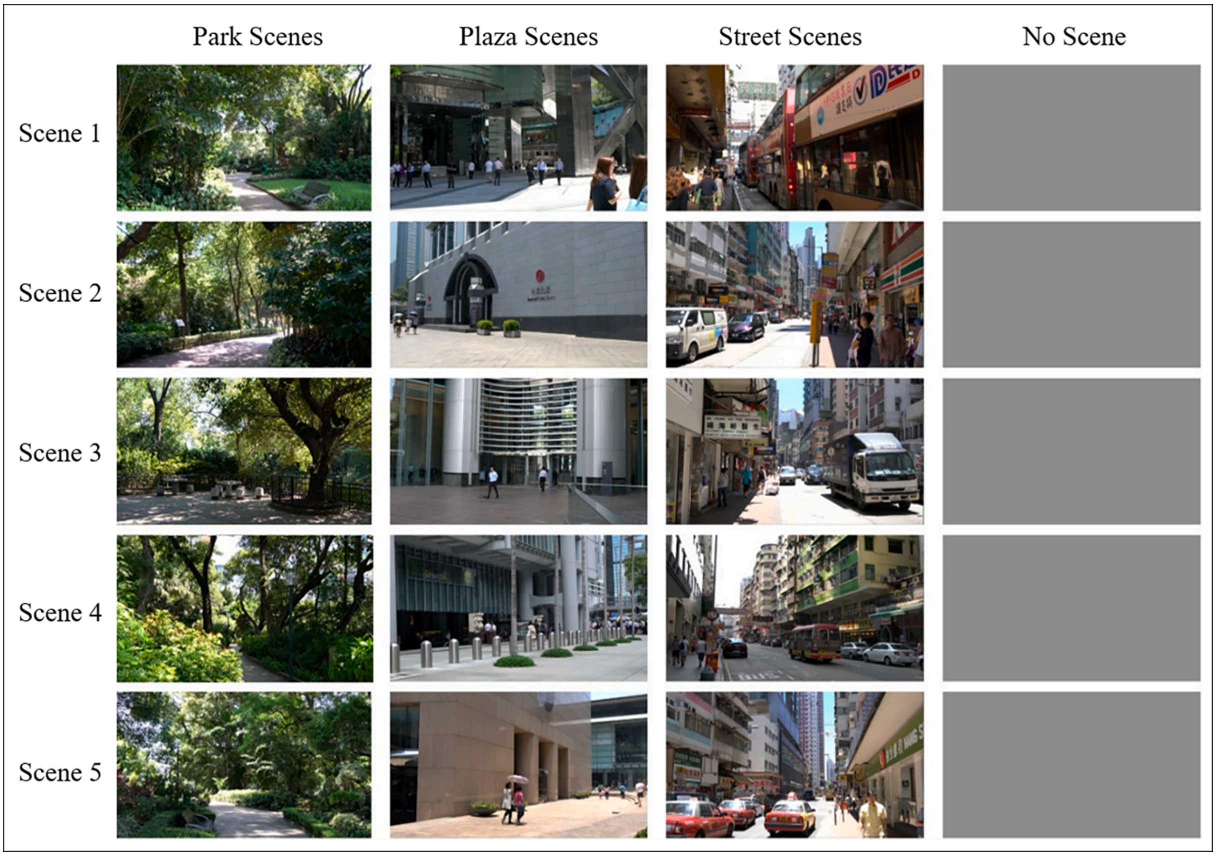

Fig. 2. Screenshots of video content showing scenes at the sampled sites.

human activities.

To ensure that the acoustic environments were as realistic as possible, we recorded sounds in real settings to play back in the lab. The on-site sounds were measured 10 m away from the sound source and recorded for at least 10 min. Traffic sounds were collected on busy major roads and the road centre line was considered as the sound source. Ventilation sounds were collected from restaurant exhaust fans with as little other sound interference as possible, and natural sounds were recorded in parks, including birdsong in the trees. The sounds were recorded with a Sony ILCE-7RM2 4 K camera.

We found it difficult to record fully natural sounds in Hong Kong, as they were often interrupted by surrounding urban noises (traffic or human voices). We therefore decided to download natural sounds from the publicly accessible website (https://www.freesfx.co.uk/soundeffects). The selected sounds were a mix of birdsong (eight of the region's common species), rustling leaves, croaking frogs, and humming insects. We deemed these to be representative of natural sounds that can be heard in high-density cities. Finally, we extracted 10-minute samples for the natural, ventilation, and traffic soundscapes.

To simulate an urban environment, where multiple sounds are typically mixed, we created combinations of the three types of sounds, with one as the dominant sound and the other two as minor: Natural Dominating sounds, Traffic Dominating sounds, and Ventilation Dominating sounds. We also included two additional categories, namely Fully Natural Sounds and No Sound, to allow us to examine the restorative effects of a wide variety of acoustic environments (Kaplan, 1995; Filipan et al., 2017).

For each of the three synthesized soundscapes, the dominant sound source was presented relatively close to the participant (10 m away) and the minor sound sources were presented farther away from the participant (100 m). We selected these distances because sound stimuli 10 m from the source are typically at an acceptable sound pressure level, while the source remains identifiable. In addition, a typical high-density urban block is 100 m long, suggesting an outer limit for the minor sounds included in each soundscape. These sounds were edited based on the equation $Lp(R2) = Lp(R1) - 20 \cdot Log10(R2/R1)$. We synthesised the audio stimuli by combining files from different tracks.

Finally, we used *Audition* software to combine the acoustic and visual stimuli. As Fig. 1 shows, we created one videos for the each of the four visual conditions (Park, Plaza, Street, and No Scene) combined with the five acoustic conditions (Fully Natural, Natural Dominating, Ventilation Dominating, Traffic Dominating, and No Sound) which resulted in 20 separate 10-minute videos. A 79″ LG Super UHD TV 79UF9500 and LG AG-F310 (X2) Cinema 3D Glasses were used to convert and display the 3D visual environments. The sounds were played through a Sony BDV-N5200W surround-sound speaker system that included a main unit, a centre speaker, a subwoofer, left and right front speakers, left and right surround speakers, and a surround amplifier (Fig. 3). We set the playback levels using the sounds of real sites as the standard to simulate authentic recording levels in the lab. The participants were seated 2 m from a 79-inch screen with the speaker system placed around them. The reproduced sound levels were measured at the height of the participants' heads when seated (Table 2 gives the acoustic characteristics of the five sound conditions).

2.3. *Measures of anxiety*

The shortened Spielberger State-Trait Anxiety Inventory (STAI) was used to measure state-trait anxiety levels (Chlan et al., 2003; Marteau & Bekker, 1992; Tluczek et al., 2009). This is a commonly used method of measuring anxiety in environment studies (e.g., Jiang et al., 2016; Jiang et al., 2019) and is a reliable and sensitive measure of anxiety (Marteau & Bekker, 1992; Spielberger, 2010; Ugalde et al., 2014). The STAI covers six items, namely 'calm', 'tense', 'upset', 'relaxed', 'content', and

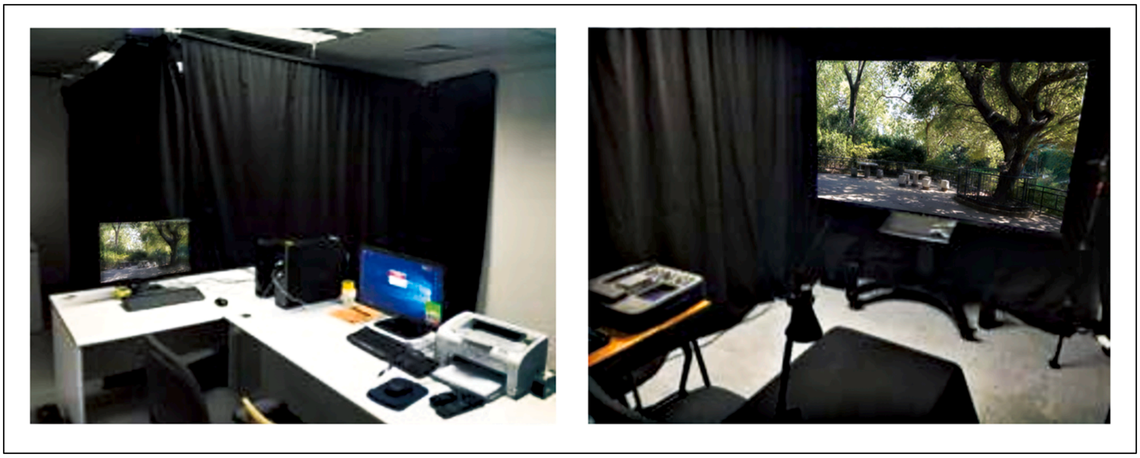

Fig. 3. Images from the virtual reality lab in which the participants were exposed to the acoustic-visual experiment (the photo on the left shows the backstage space that the participants did not see, and the photo on the right shows the experimental space).

Table 2
Descriptive statistics of the five types of acoustic environment.

Acoustic environments	LAeq/dB(A)	Lmin/dB(A)	Lmax/dB(A)
Fully Natural sounds	62.1	42.3	74.6
Natural Dominating sounds	61.4	43.9	71.1
Ventilation Dominating sounds	60.9	49.7	68.5
Traffic Dominating sounds	66.9	58.2	80.6
No Sound*	35.4	39.5	34.5

Note: * indicates that the video was muted but the acoustic characteristics of the laboratory room were measured.

'worried', each of which was measured on a continuous 11-point visual analogue scale ranging from 0 to 10, representing *not at all"* to *very much.* Three items were presented in positive terms and the remainder in negative terms. Thus, we reverse-coded the positive items so that higher scores for each item indicated more anxiety. The sum of the scores for the six items for each participant was taken as the participant's general anxiety level, and its value ranged from 0 to 60.

2.4. Procedure

Each experiment accommodated one participant (Fig. 4). When participants came to the experiment room, they first had a ten-minute rest. Then an investigator explained the experimental procedure to the participants and invited them to sign a consent form within seven minutes. After a three-minute rest, the participants reported their baseline anxiety levels (STAI_T1). Then, the participants were asked to take the Trier Social Stress Test (TSST) to induce a moderate level of anxiety (Dickerson & Kemeny, 2004; Jiang et al., 2016; Kirschbaum et al., 1993; Kudielka & Wüst, 2010; Takahashi et al., 2005; Young et al., 2004).

The TSST consists of two parts. Following this structure, the participants were first asked to make a five-minute impromptu speech as part of a mock job interview, in front of two interviewers and a video camera. They were then given five minutes to mentally solve subtraction problems without writing them down or using any calculating device. Both the face-to-face interview and the video recording induced social pressure. The TSST was applied in this study because it can both reduce the impact of distinct pre-experiment mental states (Vors et al., 2018) and induce a mental burden; thus, it has been widely used to examine the effects of environmental stimuli on various mental states (Jiang et al., 2016; Kudielka et al., 2004; MacMillan et al., 2009).

The participants reported their anxiety for the second time (STAI_T2) immediately after taking the TSST. It took 13 min to complete TSST, and first and second reports of anxiety level. They were then randomly assigned to one of the 20 environmental stimuli conditions. After viewing and/or listening to the 10-minute 3D treatment, they reported their anxiety levels for a third time (STAI_T3).

As the last step, participants spent five minutes to complete a background questionnaire. The major content of background questionnaire includes questions regarding participant's socioeconomic and demographic characteristics. In addition, participants were asked to report their perceived change of mood and tranquillity due to the exposure to acoustic-visual treatment. Each change was reported by answering a 5-point Likert question (The definitions, measures and findings of mood and tranquillity were reported as supportive evidence in Appendix G).

2.5. Statistical analysis

We analysed the changes in the participants' levels of anxiety through three steps. First, a multi-factor analysis of variance (multi-factor ANOVA) was used to measure the main and interactive effects of the acoustic and visual environments on anxiety, in which the various acoustic and visual stimuli were the categorical independent variables,

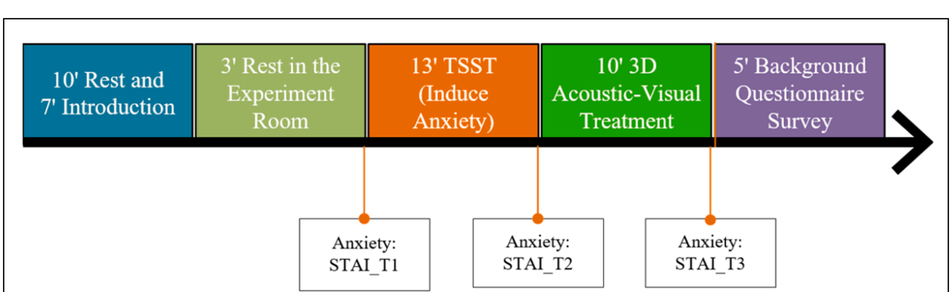

Fig. 4. Procedure and major content of the experiment.

the change in anxiety was the continuous dependent variable, and socio-demographic factors were covariates. Post-hoc analysis was used to identify differences among groups with different acoustic-visual stimuli; these were adjusted using multiple covariables. Second, to detect the independent effects of acoustic and visual environments, analysis of covariance analysis (ANCOVA) was conducted for acoustic impact at each type of visual environment, and visual impact at each type of acoustic environment, respectively, while controlling for socio-demographic factors. Third, to further observe the differences between the 20 conditions, we divided them into hierarchical groups using a k-means clustering method (Nowakowski et al., 2014). In the prototype of the clustering analysis, we partitioned *n* observations into *k* clusters, where each observation belonged to the cluster with the nearest mean. To determine how many clusters were appropriate, we conducted a within-group sum of squares test for different group sizes. We also conducted a paired comparison analysis of the differences between the control condition (no sound and no scene) and the other 19 conditions.

All the statistical analyses were conducted using SPSS 25.0, except for the K-means clustering, which was conducted using Python 3.6.

3. Results

We first report the results of tests of our questionnaire and experimental process. The interclass reliabilities of the STAI scores within six items were calculated using Cronbach's alpha. Generally, a Cronbach's alpha of 0.70 and above is good, 0.80 and above is better, and 0.90 and above is best (Landis & Koch, 1977; Xu et al., 2018). We found that the reliability of the scale exceeded the acceptable threshold at all three time points: Cronbach's alpha at T1 was 0.828; that at T2 was 0.825; and that at T3 was 0.865. We then tested whether the experimental design and process were reasonable by analysing STAI. One-way ANOVA indicated that the 20 groups were not statistically different at baseline (T1) ($F = 1.08$, $p > .10$), indicating successful random assignments. A paired samples test revealed a significant increase in STAI scores from T1 (17.96) to T2 (31.83) ($t = -20.82$, $p < .001$), suggesting that the inducement of mental burden was successful.

We next examine the extent to which the acoustic and visual environments independently and together influenced the participants' anxiety levels and determined the rank order of these effects on anxiety.

3.1. To what extent do acoustic environments and visual environments influence participants' change of anxiety?

Did the various acoustic and visual environments reduce anxiety? To answer this question, we subtracted the anxiety scores at T3 from those at T2 (STAI_T3 - STAI_T2). Thus, a higher number indicates a greater reduction in anxiety (Appendix B provides the descriptive statistics for each condition). The change in anxiety passed the normality test ($p = 0.601$, Shapiro-Wilk Test). We found that the 20 conditions had different effects, as demonstrated by the results of the multi-factor ANOVA, with an adjusted $R^2 = 0.18$, $p < .001$ (Table 3 and Fig. 5; 95 % confidence intervals of 20 conditions were presented in Appendix C). The acoustic environment significantly reduced anxiety; $F(4, 195) = 7.87$, $p < .001$, $\eta_p^2 = 0.14$). The reduction through the visual environment was marginally significant; $F(3, 195) = 2.21$, $p < .09$, $\eta_p^2 = 0.03$. A significant interaction effect between acoustic and visual environments on reducing anxiety was also found; $F(12, 195) = 1.83$, $p < .05$, $\eta_p^2 = 0.10$.

No scene and ventilation dominating sounds had the least effect on levels of anxiety ($M = 2.8$, $SD = 10.90$), while *park scenes and fully natural sounds* had the greatest effect ($M = 19.2$, $SD = 9.25$). In terms of the overall acoustic environment, *fully natural* sounds had the greatest effect on anxiety ($M = 16.8$, $SD = 9.23$), and for the visual environment, *park scenes* had the greatest effect ($M = 13.4$, $SD = 9.46$).

For acoustic environments, post-hoc analysis revealed that the *fully natural* sound condition led to a significantly greater reduction in anxiety than the other four conditions (*natural dominating sounds*, $p < .05$; *no sounds*, $p < .05$; *traffic dominating sounds*, $p < .001$; *ventilation dominating sounds*, $p < .001$); *natural dominating sounds* led to a greater reduction than *traffic* ($p < .05$) and *ventilation dominating sounds* ($p < .01$). *No sounds* led to a significantly greater reduction in anxiety than *traffic* ($p < .05$) and *ventilation dominating sounds* ($p < .01$; Table 4). For visual environments, *Park* and *Plaza scenes* led to a significantly greater reduction than *no scene* ($p < .05$), but were not significantly different from the *street scenes* (Table 5).

Fig. 5 shows that the participants' sensitivity to the sounds differed according to the three visual environments, which was reflected in change of anxiety scores. The changes in anxiety levels for *park scenes* had the highest range, from 6.2 to 19.2. For *plaza scenes*, the scores ranged from 10.0 to 15.8, and for *street scenes*, from 8.2 to 14.8. Visual environments have different sensitivity range to the sound environments, for park: 13.0, plaza: 5.8, and street: 6.6. Interestingly, no scene even had the highest sensitivity to the sounds compared to the three urban environments, from 2.8 to 18.7 (Appendix D).

3.2. To what extent do acoustic and visual environments have impacts on change of anxiety, respectively?

Results of ANCOVA showed that at parks and no scenes, acoustic environments had significant impacts on reduction of anxiety (Park scenes: *fully natural sounds* significantly better than *ventilation* (*Mean Diff.* = 13.15, $p < .001$) and *traffic dominating sounds* (*Mean Diff.* = 8.07, $p < .05$), and marginally significantly better than *natural dominating*

Table 3
Summary of the multi-factor analysis of the impact of various acoustic-visual environments on anxiety.

Source	Type III Sum of Squares	Df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	5076.04[a]	27	188.00	2.79***	0.000	0.279
Intercept	830.49	1	830.49	12.33**	0.001	0.059
Gender	397.29	1	397.29	5.90*	0.016	0.029
Age	24.85	1	24.85	0.37	0.544	0.002
Nationality	8.54	1	8.54	0.13	0.722	0.001
Marital Status	13.80	1	13.80	0.20	0.651	0.001
Density of place of birth	49.21	1	49.21	0.73	0.394	0.004
Density of residence location	8.08	1	8.08	0.12	0.729	0.001
Education	5.76	1	5.76	0.09	0.770	0.000
Income	45.63	1	45.63	0.68	0.412	0.003
Visual Environments	447.43	3	149.14	2.21ᵻ	0.088	0.033
Acoustic Environments	2120.38	4	530.10	7.87***	0.000	0.139
Visual × Acoustic	1483.67	12	123.64	1.83*	0.045	0.101
Error	13139.52	195	67.38			
Total	49937.55	223				
Corrected Total	18215.56	222				

[a] R Squared = 0.28 (Adjusted R Squared = 0.18). Note: ᵻ $p < 0.1$, *$p < .05$, **$p < .01$, ***$p < .001$.

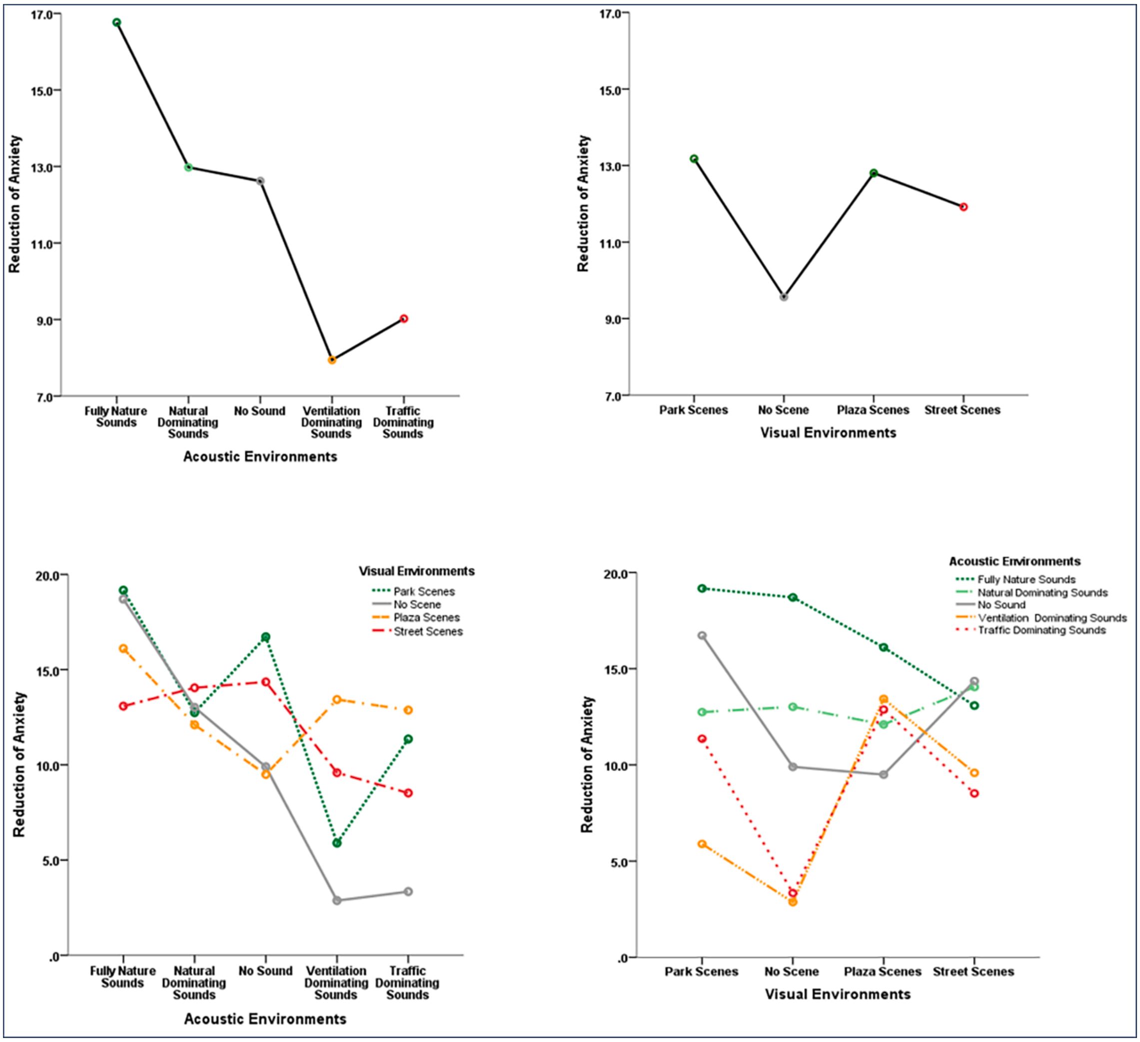

Fig. 5. Plot of multi-factor ANOVA showing the impact of various acoustic-visual environments on changes in levels of anxiety.

Table 4
Pair comparisons of changes in anxiety among acoustic environments.

	Fully Natural Sounds	Natural Dominating Sounds	No Sound	Ventilation Dominating Sounds	Traffic Dominating Sounds
Fully Natural Sounds	–	3.79*	4.15*	7.74***	8.82***
Natural Dominating Sounds		–	0.36 ^{ns}	3.95*	5.03**
No Sound			–	3.60*	4.67*
Ventilation Dominating Sounds				–	−1.08 ^{ns}
Traffic Dominating Sounds					–

Note: Mean difference = value of a row unit-value of a column unit. ^{ƚ} p <.10, *p <.05, **p <.01, ***p <.001, ^{ns}p = non-significant when $p \geq 0.1$.

Table 5
Pair comparisons of changes in anxiety among visual environments.

	Park Scenes	No Scene	Plaza Scenes	Street Scenes
Park Scenes	–	3.61*	0.38 ^{ns}	1.26 ^{ns}
No Scene		–	−3.24*	−2.35 ^{ns}
Plaza Scenes			–	0.88 ^{ns}
Street Scenes				–

Note: Mean difference = value of a row unit-value of a column unit. ^{ƚ} p <.10, *p <.05, **p <.01, ***p <.001, ^{ns}p = non-significant when $p \geq 0.1$.

sounds (*Mean Diff.* = 6.00, p <.10); *natural dominating sounds* marginally significantly better than *ventilation dominating sounds* (*Mean Diff.* = 7.16, p <.10); and *no sounds* significantly better than *ventilation dominating sounds* (*Mean Diff.* = 11.69, p <.01) and marginally significantly better than *traffic dominating sounds* (*Mean Diff.* = 6.61, p <.10). No scene: *fully natural sounds* significantly better than *ventilation* (*Mean Diff.* = 14.86, p <.001) and *traffic dominating sounds* (*Mean Diff.* = 14.57, p <.001) and *no sounds* (*Mean Diff.* = 8.59, p <.05); *natural dominating sounds* significantly better than *ventilation* (*Mean Diff.* = 10.51, p <.01) and *traffic dominating sounds* (*Mean Diff.* = 10.21, p <.05); and *no sound* marginally significantly better than *ventilation dominating sounds* (*Mean Diff.* = 6.27, p <.10)), while non-significant effects of acoustic environments were found at plazas and streets. For visual effects, in no sound, ventilation and traffic dominating environments, visual impacts were significant (No sound: *park scenes* significantly better than *no scene* (*Mean Diff.* = 6.92, p <.05) and *plaza scenes* (*Mean Diff.* = 9.79, p <.01); and *street scenes* marginally significantly better than *plaza scenes* (*Mean Diff.* = 6.71, p <.10). Ventilation dominating sounds: *plaza scenes* significantly better than *no scene* (*Mean Diff.* = 10.46, p <.01) and marginally significantly better than *park scenes* (*Mean Diff.* = 7.80, p <.10); and *street scenes* marginally significantly better than *no scene* (*Mean Diff.* = 7.66, p <.10). Traffic dominating sounds: *park* (*Mean Diff.* = 8.58, p <.05) and *plaza scenes* (*Mean Diff.* = 11.26, p <.01) significantly better than *no scenes*). However, in fully nature or natural dominating environments, visual impacts on reducing anxiety were non-significant. The results indicated that in natural visual environments (for example, parks), acoustic impacts are more essential for reducing anxiety; while in natural sound environment, visual plays less significant role in reducing anxiety, but visual impact is essential for the place with artificial sound environments (for example, ventilation and traffic sounds).

3.3. The rank order of the effects of the 20 acoustic-visual environments on change of anxiety

The results of the six groups of acoustic and visual environments for change in anxiety are shown in Table 6. The first and second groups have four conditions with either *fully natural sounds* or *park scenes* and yielded significant or marginally significant restorative effects, compared with the control condition. *Park scenes and fully natural sounds* was the most restorative condition. The sixth group included two "*no scene*" conditions with either *traffic* or *mechanical sounds*, and their restorative effects were significantly or marginally significantly worse than those of the control condition.

4. Discussion

This study revealed the effects of various pairs of acoustic-visual environments on anxiety in the context of a high-density city. We first assess how our findings address our key research questions. We then discuss the implications for planning and design. Finally, we consider the limitations of our study and directions for future research.

Table 6
Ranking of anxiety relief for the six clusters and pair comparisons between the 19 conditions and the neutral (control) group.

Anxiety	Acoustic-visual environments (20 conditions)	Mean	Mean diff.
1	Park Scenes & Fully Natural Sounds	19.23	9.27**
	No Scene & Fully Natural Sounds	18.65	8.81*
2	Park Scenes & No Sound	16.69	6.83 ǂ
	Plaza Scenes & Fully Natural Sounds	15.75	6.21 ǂ
3	Street Scenes & Natural Dominating Sounds	14.83	4.15
	Street Scenes & No Sound	14.55	4.46
	Plaza Scenes & Ventilation Dominating Sounds	13.44	3.53
	Street Scenes & Fully Natural Sounds	13.43	3.19
	No Scene & Natural Dominating Sounds	13.06	3.12
4	Plaza Scenes & Traffic Dominating Sounds	12.35	2.98
	Plaza Scenes & Natural Dominating Sounds	12.15	2.21
	Park Scenes & Natural Dominating Sounds	12.1	2.85
	Park Scenes & Traffic Dominating Sounds	11.54	1.46
	No Scene & No Sound (control group)	**10.05**	**±0.00**
	Plaza Scenes & No Sound	9.98	−0.4
5	Street Scenes & Ventilation Dominating Sounds	9.64	−0.31
	Street Scenes & Traffic Dominating Sounds	8.17	−1.38
	Park Scenes & Ventilation Dominating Sounds	6.17	−4.01
6	No Scene & Traffic Dominating Sounds	3.03	−6.56 ǂ
	No Scene & Ventilation Dominating Sounds	2.83	−7.03*

Note: The mean descriptive statistics are of the change in anxiety for the acoustic-visual environments estimated as the marginal mean. Each pair comparison between the acoustic-visual environment and the control group are adjusted using an independent variable (acoustic-visual condition) and multiple confounding factors (see Table 1 for details). Pair comparisons between acoustic-visual environments and the control group are based on estimated marginal means; 95 % CI denotes 95 % confidence interval for difference; ǂ p <.10, *p <.05, **p <.01.

4.1. The acoustic and visual environments significantly influence anxiety relief

We find that both acoustic and visual environments have significant effects on anxiety, as extensively reported in previous studies (Ohno & Matsuda, 2013; Wang et al., 2022; Yin et al., 2020; Zhou et al., 2020). Further, we find that in natural visual environments, acoustic impacts are significantly different for reducing anxiety, depending on types of acoustic environments; while in artificial sound environment, visual impacts are significantly different in reducing anxiety, depending on types of visual environments. However, their combined effects on anxiety relief have rarely been examined in the context of high-density cities. Our finding of significant interactive effects from acoustic and visual environments is consistent with the natural acoustic and visual impacts on anxiety identified in healthcare settings (Watts et al., 2016). They also support studies indicating such interactive effects on mental restoration (Zhao, Xu, et al., 2018), positive mood states (Jiang et al., 2021), and stress reduction (Park et al., 2020) in urban environments.

The observed effects in this study can be interpreted as based on sensory interaction. Research on sensory interactions has reported additive or facilitatory aspects of acoustic-visual interactions: acoustic stimuli can enhance the perceived intensity of visual stimuli, as measured in terms of resulting behaviour (Farida, 2007). The pooling of neural signals from multimodal stimuli has been found to induce facilitatory interactions of these signals in human brains (Meredith & Stein, 1983). These findings suggest that the synergetic effects of visual and acoustic stimuli are greater than the sum of the effects of their individual stimuli, which can help us to understand the effects identified in this study.

4.2. Stronger effects of acoustic environments than visual environments on anxiety relief

Although many studies have highlighted the impact of the visual environment on anxiety, we found that acoustic environments had an effect 4.67 times greater (number is calculated from Partial Eta Squared of visual and acoustic environments in Table 3). Our various senses are found to have comparative advantages in terms of information processing or acquisition, due to their different physiological functions (Heron et al., 2004). Information collected visually from the surrounding environment may have a greater effect than that collected from other senses (Gan et al., 2014), but it is not always dominant, particularly in terms of its effect on reducing anxiety.

Researchers have found that acoustic stimuli may be more effective than visual stimuli at eliciting various mental responses and states, such as stress states (Hedblom, Gunnarsson, Iravani, et al., 2019), multidimensional mood states (Jiang et al., 2021), and psychological restoration (Ma & Shu, 2018). The acoustic preferences in a landscape evaluation were found to be 4.5 times more important than visual preferences (Gan et al., 2014). Thus, sound has an important role in influencing perceptions of landscapes and can provide mental health benefits. In addition, some auditory stimuli may reduce the influence of visual perceptions on anxiety more than one might expect. Evidence of an auditory suppression effect on visual perception has been offered (Hidaka & Ide, 2015), and of degradations in visual performance due to auditory stimuli (Malpica et al., 2020). Researchers argue that temporal perception (mainly through sound) in contemporary cities may have more of an impact on environmental information processing than spatial perception (mainly through vision). However, the mechanisms of the links between visual and acoustic senses are not fully understood, and thus further research is required.

4.3. Key natural characteristics for anxiety relief

In general, we identified a clear trend: environments with more natural features, either acoustic or visual, had stronger positive effects on anxiety than those with a greater presence of anthropogenic elements. These findings are consistent with studies of the effects of natural elements on anxiety (Ulrich, 1981; Wang et al., 2022; Yin et al., 2020; Zhang et al., 2023; Zhou et al., 2020) and of multiple mental states, such as improved mood (Jiang et al., 2021); stress reduction (Zhang et al., 2023); psychological well-being (Ulrich, 1979) and mental restoration (Jahncke et al., 2015; Ratcliffe, 2021). However, two novel findings on how natural characteristics improve mental restoration are worthy of special attention.

4.3.1. Natural scenes lead to more sensitive responses to sounds than artificial scenes

The anxiety relief effects of natural scenes (*park scenes*) show high sensitivity to combined sounds compared to the other artificial scenes (*plaza scenes: 2.26 times* and *street scenes: 1.96 times, see* Appendix D). Meanwhile, acoustic environments have significantly different impacts on reducing anxiety in parks, while no significantly different acoustic impacts are found in plazas and streets (see Section 3.2 for details). This suggests that the anxiety relief effect of visually "green" environments can be increased by combined natural sounds. Conversely, the relief effect of visually "barren" environments can be improved by natural sounds but only to a limited degree. This difference in sensitivity is partially supported by previous findings. For example, natural sounds have been found to increase the restorative benefits of parks or other natural environments (Buxton et al., 2021), but in urban streets or plazas with less greenery, they can do little to mask the sounds of noisy traffic (Hao et al., 2016), which means that they cannot effectively provide restorative and health benefits in urban environments. Although there is evidence that sounds are critical to the perception of how nature-friendly an urban space is (Jeon & Jo, 2020), the same type of sound may lead to different perceptions, depending on the visual environments it interacts with. The incongruence between an urban visual setting and an aural setting dominated by natural sounds may lead to this, or if natural and artificial sounds are combined (Carles et al., 1992; Deng et al., 2020; Xu & Wu, 2021; Zhao, Xu, et al., 2018). Or some sound characteristics may also override or mask others (Hedblom et al., 2019b). Our findings together provide a greater understanding of the mental restoration effect of acoustic-visual environments.

4.3.2. Fully natural sounds are more effective for anxiety relief than natural dominating sounds

The effects of a single dominant sound and a whole soundscape on perceptions of the acoustic environment (Pérez-Martínez et al., 2018) and emotional perceptions (Xu et al., 2019) have been identified. However, the distinct effects of fully natural and natural dominating sounds on mental improvement should not be neglected (Table 4 and Appendix E). For example, the fully natural sounds of the park scenes imply a different environmental context from that in which natural sounds dominate, as they provide the experience of being far away or insulated from developed urban areas, with virtually no disturbance from urban noise. Contexts with multiple sounds but in which natural sounds dominate, although "visually" natural, are more or less adjacent to developed urban areas or are not designed to fully mask nearby noises. Kaplan's attention restoration theory suggests that the perception of "being away" is critical for mental restoration (Kaplan, 1995). This refers to the perception of being separated from one's normal life, which includes possibly mundane living environments. Compared with a mixed acoustic environment, being in a fully natural acoustic environment can better "transport one elsewhere in mind" (Kaplan, 2001, p. 511). These significant positive effects of "being away" on mental states have been identified in many studies of visual and/or acoustic environments (Alvarsson et al., 2010; Chang et al., 2008; Korpela et al., 2001; Panno et al., 2020).

4.4. Important phenomena revealed by ranking the anxiety relief effects of 20 acoustic-visual environments

Although our ranking analysis suggests that more natural environments yield greater reduction in anxiety compared to the control group, we caution our readers that we examined only one high density city and the natural settings within that city. These findings should be replicated in different high-density cities using visual and auditory stimuli that are appropriate for the locale. If the findings presented here are replicated, we will have greater confidence that combined acoustic and visual stimuli that portray natural environments will have salutary impacts on anxiety.

In this specific study, we found that natural stimuli yielded better effects of anxiety relief than artificial stimuli. The combination of green scenes and fully natural sounds was more anxiety relieving than any of the other acoustic-visual environments (see Appendix F for pairwise comparisons between each pair of 20 treatments). Viewing natural scenes or hearing fully natural sounds can also be beneficial for anxiety relieving. As a contrast, artificial noises are detrimental to anxiety relief, and not all their adverse effects can be reduced by introducing natural scenes. All these findings suggest a clear trend that natural acoustic and natural visual environments provide effects of anxiety relief. Urban residents have a strong desire for contact with nature and this is a form of psychological restoration and thus an important protection of urban residents' mental health (Jiang et al., 2015; Van den Berg et al., 2007). However, the investigation of diverse combinations of acoustic and visual environments cannot be done by this single study and many more studies should be conducted to fully understand the possibilities of combinations, ranking of those combinations, and the meaning of the ranking.

4.5. Planning and design implications

Based on the findings of this study, we offer the following suggestions to create healthy acoustic and visual environments in high-density cities.

Both visual and acoustic elements should be considered when designing anxiety-relief public spaces in high-density cities. The positive effects of natural acoustic and/or visual environments should not be neglected. Thus, attention should be paid to the site acoustics and visual elements and the relationships between them, so that urban planners and designers can optimise environmental resources to create healthy cities.

Planners and designers often emphasise the effects of the visual environment on anxiety relief, but they largely ignore the significant role that acoustic environments can play. Our findings suggest that the benefits derived from nature can be ascribed to both visual and acoustic elements. According to significant and strong acoustic impacts of on reducing anxiety, we urge planners and designers to pay more attention to creating acoustic environments, especially natural sounds, which contributes to relieve anxiety.

The anxiety-relief effects of natural scenes were influenced more by accompanying sounds than were the anxiety-relief effects of artificial scenes. Natural sounds should be carefully provided or preserved in green spaces. Practical design approaches such as the addition of vegetation, noise walls, or earth berms or reducing sound activities at source can be applied to reduce unwanted noise (Brown, 2012). Adding natural sounds to barren urban spaces may also be helpful, but the additional restorative effect is likely to be limited. It is vital to add vegetation that can be accompanied by the sounds of nature.

While natural dominating sounds can also promote anxiety relief, we found that fully natural sounds had the greatest benefits. To maximise the benefits of fully natural sounds, the construction of sound environments should be considered in the early stages of urban development or redevelopment (Kang et al., 2016). Creating or preserving large green spaces such as urban parks and forests is important because such spaces can provide habitats for mammals and insects, a major source of audible natural sounds, and create an effective buffer from anthropogenic sounds.

4.6. Limitations and suggestions for future studies

Several limitations of our research design could be addressed in future studies.

First, in real high-density urban settings, continuous and diverse changes in the built environment makes it difficult to precisely calculate sound transmission. Thus, a single study cannot simulate all possible combinations of transmission distances or of anthropogenic and natural sounds. More studies on various acoustic and visual environments are still needed in other high-density cities to identify the optimal rankings and to provide general findings for the development of planning and design methodologies widely.

Second, individuals' perceptions of their environments can arouse multiple sensory reactions. Although we explored the impact of acoustic and visual stimuli on individuals' auditory and visual senses, perceptions of the environment can also be prompted through olfactory and tactile means (Franco et al., 2017; Zhao et al., 2018a). Therefore, we suggest that future studies should duplicate this study in more immersive and multi-sensory lab environments or even in real environments. Other aspects of mental states can also be investigated to enrich research on this topic.

Third, our study was conducted in Hong Kong. Although Hong Kong is an international city with modern urban scenes and we intentionally selected acoustic and visual stimuli that are common to many other high-density cities across the world, researchers should still duplicate this study in other regions to enhance the generalizability of our findings.

Fourth, individual noise sensitivity has a significant effect on the evaluation of the urban environment, and thus may affect anxiety recovery (Jo et al., 2022). Although the random assignment we applied is regarded as an effective method of mitigating individual differences among participants, future studies can benefit from measuring individual noise sensitivity as pre- and post-tests.

Finally, the findings related to mood and tranquillity show considerable agreement with the results for anxiety. However, we emphasize that the main objective of this study was to investigate the effects of acoustic-visual environments on anxiety. To achieve this objective, the instrument and procedure utilized to measure anxiety were designed in a more comprehensive and rigorous manner than those employed to assess mood and tranquillity. Our focus in this article is primarily on introducing and interpreting the findings related to anxiety. We recommend that future studies adopt rigorous measures to investigate the relationship between different aspects of mental health and develop a more holistic understanding of the impact of acoustic-visual environments on mental health (Refer to Appendix G for findings related to mood and tranquillity).

5. Conclusion

In this study, we examined the independent and interactive effects of acoustic and visual environments on anxiety in the context of a high-density city. We are positive that this study can provide solid and specific scientific evidence to support planning and design of urban environments, which can help hundreds of millions urban dwellers who are suffering from the anxiety disorder in the world.

CRediT authorship contribution statement

Wenyan XU: Methodology, Software, Formal analysis, Investigation, Visualization, Writing – original draft, Writing – review & editing. **Huaqing WANG:** Investigation, Methodology, Data curation. **Hua SU:** Methodology, Writing – review & editing. **William C. SULLIVAN:** Methodology, Writing – review & editing. **Guangsi LIN:** Writing – review & editing. **Mathew PRYOR:** Methodology. **Bin JIANG:** Conceptualization, Methodology, Funding acquisition, Project administration, Resources, Supervision, Data curation, Formal analysis, Investigation, Validation, Visualization, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.landurbplan.2023.104927.

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