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**Highlights**

- Auditory-olfactory restoration was compared in visually impaired and sighted users.
- Visual impairment shaped restoration levels and physiological response patterns.
- Sounds of water, birds and music consistently enhanced psychological restoration.
- Odour effects and sound-odour interactions were generally modest.
- Findings inform inclusive multisensory design for urban public spaces.

# Comparative Effects of Auditory-Olfactory Environments on Restoration in Visually Impaired and Sighted Individuals in Urban Public Spaces

Meihui BA<sup>a</sup>, Weihang XU<sup>a</sup>, Zhongzhe LI<sup>a\*</sup>, Jingyu FANG<sup>a</sup>, Jian KANG<sup>b</sup>

<sup>a</sup>Pan Tianshou College of Architecture, Art and Design, Ningbo University, Ningbo, China.

<sup>b</sup>UCL Institute for Environmental Design and Engineering, The Bartlett, University College

London (UCL), London, United Kingdom.

\*Corresponding Author: lizhongzhe@nbu.edu.cn, Pan Tianshou College of Architecture, Art and Design, Ningbo University, Ningbo 315211, China.

Email addresses: bameihui@nbu.edu.cn (M. Ba), x0071200@163.com (W. Xu),

lizhongzhe@nbu.edu.cn (Z. Li), 18110817660@163.com (J. Fang), J.kang@ucl.ac.uk (J. Kang)

**Abstract:** Restorative-environment research remains visually centred, leaving unclear whether auditory-olfactory environments produce comparable restorative responses in visually impaired and sighted individuals. A laboratory-based randomised incomplete-block experiment included 76 participants (36 visually impaired and 40 sighted), each completing seven scenarios drawn from 42 sound × odour combinations. Psychological restoration was assessed using four Perceived Restorativeness Scale domains, and nine physiological outcomes were expressed as percentage changes from resting baselines. Paired comparisons assessed overall group differences, while trial-level linear mixed-effects models assessed condition effects and between-group differences in response patterns. Visually impaired participants showed higher Being-away, Fascination, and Coherence scores (Cohen's  $d_z = 0.34 - 0.69$ ), together with higher heart rate variability ( $d_z = 0.44$ ) and lower respiration rate ( $d_z = -0.36$ ). No vision interactions were detected for psychological outcomes. In both groups, sound significantly affected all four psychological outcomes, whereas

odour and sound  $\times$  odour did not show significant omnibus effects. Water, birds, and music were generally associated with higher restoration scores, while hawking and children's sounds were associated with more favourable responses among visually impaired participants. Physiological effects were sparse and indicator-specific. Selected vision interactions were detected, but most two-way effects were small and some were influence-sensitive. Group-specific effects comprised a tentative sound effect in high-frequency components of the heart rate variability power spectrum among visually impaired participants and clearer effects in heart rate and respiration depth among sighted participants. These findings distinguish overall group differences from condition-response patterns and support auditory-led, context-sensitive multisensory design in inclusive urban public spaces.

**Keywords:** visual impairment; auditory environment; olfactory environment; restorative environment; multisensory experience; urban public spaces

## 1 Introduction

Vision impairment, which ranges from reduced visual acuity or restricted visual fields to complete loss of vision, is a major global public health issue. The World Health Organization estimates that at least 2.2 billion people live with vision impairment [1]. Although the population of visually impaired individuals is large, the loss of visual function means that this group is more likely to experience psychological and physiological stress arising from difficulties in environmental adaptation, social exclusion, and insufficient self-efficacy, while also limiting their everyday urban activities and social participation. In this context, urban public spaces, including courtyards, pedestrian areas, parks, plazas, and city squares, frequently constitute important arenas for the daily activities and social interaction of individuals with visual impairments, and the environmental quality of these spaces substantially influences their lifestyles [2]. However, existing research on the environmental quality of urban public spaces and related health-oriented design remains largely visually centred and focused on sighted individuals. This can easily lead to 'one-size-fits-all' solutions beneficial for some people but ineffective or even harmful for others,

reducing the equity and transferability of spatial interventions. Therefore, creating high-quality urban public spaces accessible and supportive for both visually impaired and sighted individuals not only enhances the inclusiveness of the urban environment, but also encourages visually impaired people to engage more fully in everyday life and social interaction.

Restorative environments can promote physiological recovery, positive emotional states, stress relief, attention restoration, and psychological well-being [3-6], and have received increasing attention in environmental psychology, urban and architectural design, and public health [7-9]. These restorative effects are commonly explained by two complementary frameworks: Attention Restoration Theory (ART), which emphasises recovery from directed attention fatigue and restorative qualities such as being away, fascination, coherence, and compatibility [10,11], and Stress Recovery Theory (SRT), which focuses on affective and physiological stress recovery through autonomic regulation involving sympathetic and parasympathetic activity [12,13]. Because ART and SRT describe related but distinct restorative processes, restoration in urban public spaces should be assessed through both subjective perceived restorativeness and physiological indicators such as heart rate, heart rate variability, respiration, and skin conductance [14-16].

Current research on the restoration of urban spaces has primarily focused on visual characteristics such as spatial depth, openness, visual complexity, prospect, and refuge [17-19]. However, for visually impaired individuals, audition and olfaction serve as important media for perceiving the urban spatial environment, and taste and touch are more active forms of sensory engagement that rely more heavily on individual intention [20]. Therefore, the restorative effects of urban public spaces may be strengthened through the targeted design of auditory and olfactory environments, which would more comprehensively enhance the shared spatial experience between visually impaired and sighted individuals. Many studies have confirmed the restorative effects of urban auditory environments on sighted individuals [21-23]. The Perceived Restorativeness Soundscape Scale (PRSS) adapts restorative-environment concepts to auditory environments and is widely used to assess soundscape restoration, particularly when restoration is primarily attributed to auditory cues [24]. The spatial settings of these studies are mostly urban parks, green spaces, and waterfront spaces, and the sound types investigated primarily natural sounds [25-27].

Natural sounds such as birdsong and water sounds are often linked to relaxation, positive affect, and perceived restoration [28-30], but their effects depend on context: birdsong varies by species and spatial congruence [31,32], while water sounds may be less beneficial when nearby noise is highly variable or intrusive [33]. Urban sounds have more heterogeneous and context-dependent restorative qualities than natural sounds, with their effects influenced by social interaction, familiarity, expectations, and the activities taking place in the surrounding environment [34].

Compared with sighted individuals, visually impaired participants may place greater emphasis on functional aspects of the auditory environment, as sound supports orientation and identification and provides environmental and situational awareness [35]. The evaluation of various urban auditory environments by visually impaired individuals involves indicators such as clarity, comfort, safety, vitality, and depression [36]. Furthermore, these demands vary significantly across different types of urban spaces [36,37]. This suggests that the dependence of visually impaired individuals on auditory environments may not only alter their subjective evaluations, but may also influence the way in which restoration occurs. In research on restorative environments, Shaw et al.'s interview-based study found that visually impaired individuals' restoration in natural environments was achieved mainly through auditory stimuli, with olfactory and tactile cues playing secondary roles, and that perceived safety was a critical prerequisite for this non-visual restorative process [38]. These studies suggest that auditory environments may be especially important for visually impaired individuals' restoration, but whether auditory cues produce shared or group-specific psychological and physiological responses in visually impaired and sighted individuals remains unclear.

Olfactory environments have received less attention than auditory environments in restorative research, with built-environment studies focusing more on odour pollution, malodour, air quality, and nuisance control than on restorative potential [39,40]. Research on urban olfactory environments has emphasised that odours are characterised by strong contextuality, intermittency, and associations with memory, and closely related to a sense of place, identity, and emotional experience [39]. Commonly examined natural odours include floral scents, grass, soil or earthy smells, and water-related smells, whereas urban odours include food and cooking smells, traffic-related emissions, and other malodorous sources [39-41]. Regarding restorative evidence, studies

have indicated that natural odours are generally associated with reduced stress, enhanced relaxation, and improved well-being; consequently, scholars have advocated incorporating natural odours into strategies for urban nature exposure and health promotion [41-43]. Concurrently, experimental research has begun to incorporate olfaction as a controllable variable into multisensory nature exposure, demonstrating that olfactory cues can substantially contribute to restorative outcomes and jointly shape restorative experiences alongside visual and auditory stimuli [44]. For visually impaired individuals, studies that directly treat the olfactory environment as an independent variable and examine restorative outcomes are limited. Shaw et al. reported that olfaction can also serve as a source of restorative experience in certain contexts, although it is secondary to sound [38]. In a study evaluating park restoration, Boucherit et al. included smell-related items. They reported that visually impaired individuals were more sensitive to perceiving particular smells in parks [45]. These studies suggest that olfactory cues may contribute to restoration, but their effects remain less systematically examined than visual and auditory environments, particularly as controllable experimental variables.

The sensory modalities do not operate independently, but interact with one another. Crossmodal research has shown that auditory stimuli can alter judgements of odour quality, and vice versa, indicating that hedonic congruence and crossmodal correspondences can influence the evaluation of olfactory cues and emotional responses [46]. In urban contexts, odours have been shown to modify overall evaluations of traffic environments [47]. Laboratory studies have also identified mutual masking and evaluative coupling between sound and odour, and in some cases, the influence of odour on sound evaluation is stronger than that of sound on odour evaluation [20]. Multisensory pollution research that more closely reflects real urban stressors has demonstrated that sound and odour jointly influence both physiological and perceptual outcomes [48]. This highlights the need to consider the interactive effects of these two sensory channels in design. In addition, research on auditory-olfactory interaction in urban open spaces has indicated that food-related odour can improve acoustic comfort and environmental congruency, whereas unpleasant odour can worsen traffic-related evaluations [49]. These findings reveal the structural role of smellscape in the urban environmental experience. Overall, research on the restorative effects of olfactory environments among sighted individuals is gradually forming a consensus that natural

smells are generally associated with beneficial outcomes, and their effects on experience are often shaped by context and multisensory integration [41,44].

Methodologically, studies of auditory-olfactory and other multisensory environments commonly use field observations, soundwalks and smellwalks, surveys, interviews, laboratory experiments, and VR simulations [42,50]. Field methods offer ecological validity, whereas laboratory and VR methods provide greater control over sound and odour presentation, which is important given the difficulty of standardising olfactory concentration, diffusion, duration, adaptation, and removal [42,51]. However, existing auditory-olfactory studies have mainly focused on sighted participants, overall environmental evaluation, or single perceptual outcomes, leaving unclear whether such interactions produce shared or group-specific restorative responses in visually impaired and sighted individuals.

Based on the above review, the key gap is that visually impaired individuals remain underrepresented in restorative environment research, and few studies have directly compared visually impaired and sighted individuals under the same auditory-olfactory conditions. It therefore remains unclear whether these non-visual cues produce shared or group-specific patterns of psychological restoration and physiological regulation. This study therefore used urban public spaces as the context and conducted a laboratory-based simulation in which VR visual stimuli, headphone-delivered sounds, and controlled odours were presented in random sound-odour combinations. Psychological restoration and physiological regulation were measured to compare visually impaired and sighted participants and to examine whether visual status influenced responses to sound, odour, and their combinations. The research questions are as follows: (1) Do visually impaired and sighted participants differ in overall psychological and physiological restoration in simulated urban public spaces? (2) How do sound, odour, and their combination affect psychological restoration in each group? (3) How do sound, odour, and their combination affect physiological restoration in each group?

## 2 Methods

This laboratory study used a randomised incomplete-block design to compare restorative

responses in visually impaired and sighted participants. The full condition pool comprised 42 Sound×Odour combinations (seven Sound × six Odour, including controls), but each participant completed seven randomly assigned combinations. Visual status was the between-participant factor, and repeated Sound×Odour exposures constituted the within-participant component. Trial-level analyses retained the assigned condition of each observation and accommodated unequal realised cell sizes. The controlled laboratory setting enabled standardised presentation of VR, auditory, and olfactory stimuli and collection of psychological and physiological outcomes. Overview of the study design is shown in Fig. 1.

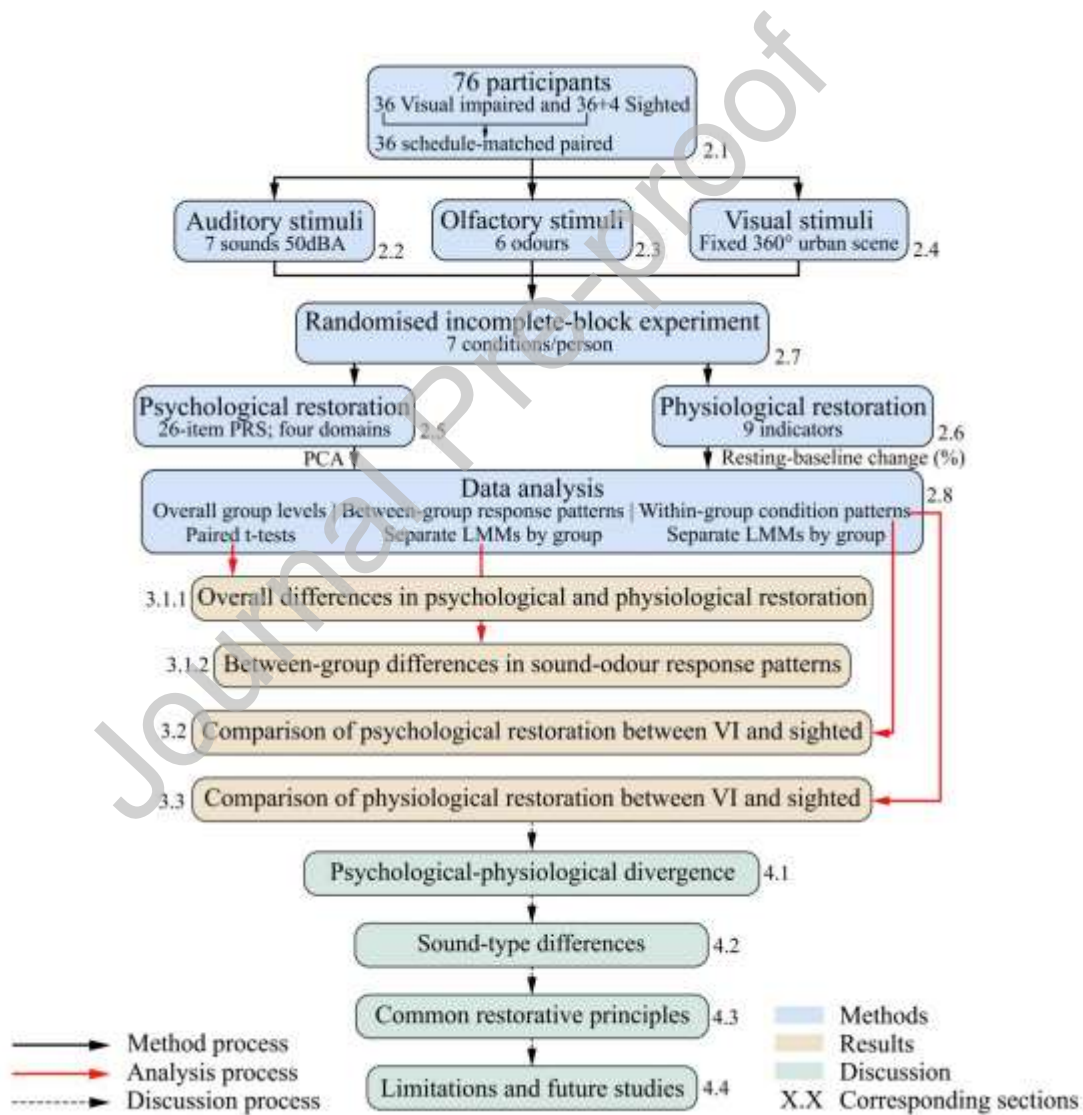


Fig. 1. Overview of the study design

## 2.1 Participants

The preliminary semi-structured interviews on restorative auditory and olfactory stimuli involved 25 participants with Grade I visual disability (defined under the Chinese national classification as no light perception to best-corrected visual acuity below 0.02, or a visual-field radius below 5°), none of whom participated in the formal experiment. They were 18 – 60 years old (12 women and 13 men) and were recruited through online non-profit organisations serving visually impaired people. Trial-level analyses included 76 compensated participants: 36 visually impaired and 40 sighted participants. All visually impaired participants had Grade I visual disability, and were analysed as a single severe visual-impairment group. All visually impaired participants met this criterion and were recruited through a local visually impaired association, while sighted participants were recruited from the general public and matched as closely as possible by sex and age. All participants reported normal hearing and olfaction, no psychotropic medication use, and no history of cardiac or respiratory disease. They refrained from wearing perfume, smoking, and vigorous physical activity during the 2 h before the experiment. Further participant and sampling details are provided in Appendix A. The complementary participant-level analysis was restricted to 36 prespecified visually impaired-sighted pairs who received identical seven-condition schedules in the same presentation order; the four additional sighted participants were included only in the mixed-effects models, which accommodated unequal group sizes and did not require cross-group pairing. Although no formal a priori power analysis was conducted because recruitment of eligible visually impaired participants was constrained, the repeated-measures dataset was adequate for the prespecified analyses, and model diagnostics and sensitivity analyses supported the robustness of the results (Appendix G).

## 2.2 Auditory stimuli

Auditory stimuli were selected through semi-structured interviews on restorative sounds and odours with 25 Grade I visually impaired individuals who did not participate in the formal experiment. Sounds mentioned by more than half of the interviewees and representing common sources in urban public spaces were retained. The final set comprised six restorative sounds—

birds, water, rustling leaves, children, hawking, and non-lyrical light music—covering natural, anthropogenic, and artificial sources, together with a background-control condition without a dominant sound source. Children and hawking were included because interviewees associated them with vitality, everyday social activity, and a lively public-space atmosphere. The music condition used widely preferred non-lyrical light music from highly ranked online tracks, and the background control represented an open public space without a clearly dominant sound source.

Sound materials were recorded from early to late morning in urban public spaces in China, using a BHS II binaural headset connected to an SQobold portable recording system (HEAD acoustics), when the designated source was dominant and unrelated transient interference was minimal. During field recording, the binaural microphones were positioned approximately 1.5 m above ground and at least 1.5 m from reflective surfaces. Each stimulus was a continuous 120-s stereo excerpt without internal deletion and looping, and only identical constant gain was applied to both channels. During playback through WH-CH720N headphones (Sony) mounted on a HMS IV.0 artificial head (HEAD acoustics), the left-ear A-weighted equivalent continuous sound pressure level over 2 min ( $L_{Aeq,2min}$ ) was adjusted to 50.0 dB(A), and the right channel was not adjusted independently. This level was selected because it could be clearly perceived in the laboratory without being overly loud, and it allowed sound conditions to be presented at a moderate and comparable level [52]. Although 50 dB(A) is below many outdoor urban levels, reduced-level laboratory playback can produce perceptual responses closer to in-situ experience than playback at the original field level [53]. Details of the specific recording sites, auditory-stimulus selection, interview procedures, field recording, stimulus preparation, playback-level calibration, frequency spectra, and loudness are provided in Appendix B.

### 2.3 Olfactory stimuli

Olfactory stimuli were selected using the interview-based criteria described above. Five restorative odours—grass, osmanthus, soil, hotpot, and coffee—were included, together with a no-odour control. Essential oils with high perceived authenticity were used because they could be precisely diluted to provide controlled odour concentrations [20]. The diluted solutions were

evenly applied to medical cotton balls placed at the bottom of 200-mL glass beakers, which were positioned 45 cm from the participant's nose to maintain consistency in odour delivery across participants and conditions [20,37]. Following previous auditory-olfactory laboratory procedures, five dilution levels were pilot-tested for each odour, and the level rated closest to moderate intensity was selected for the formal experiment [20,37]. To approximate simultaneous auditory and olfactory onset, grass and osmanthus were opened 10 s in advance, whereas soil, hotpot, and coffee were opened 5 s in advance. Detailed information on the odour materials, concentration calibration, sample preparation, and presentation procedures is provided in Appendix C.

## 2.4 Visual stimuli

A typical open space in an urban residential community in China was selected as the visual stimulus for this study. The 360° panoramic video was recorded in the morning using a panoramic camera (Insta360 ONE X2). The scene incorporated multi-storey residential buildings, green spaces, and a water feature. Within the scene, the artificial stream was 1.8 m wide, and a wooden viewing platform and pergola were located beside the water. A complete equirectangular frame providing a clearer view of the visual environment is provided in Appendix C. The same visual scene was used across all experimental conditions to provide a consistent visual context. The video materials contained no distracting events or pedestrian activity, and did not include visible sources corresponding to the sound or odour stimuli. This design allowed the auditory and olfactory conditions to be varied while keeping the visual environment constant across scenarios, and also reflected the experimental situation in which the auditory and olfactory sources were not visually identifiable. The visual stimuli were presented through a VR headset (HTC Vive Pro 2), with spatial positioning provided by base stations (HTC SteamVR Base Station 2.0). To keep the external presentation conditions consistent across participant groups, the same VR-based visual-presentation procedure was applied to both visually impaired and sighted participants.

## 2.5 Psychological restoration measurements

Psychological restoration was assessed using Hartig et al.'s revised 26-item Perceived

Restorativeness Scale (PRS) [54], an extension of the original scale [55] with broader dimensional coverage, clearer item wording, and a more stable factor structure. Although the PRSS is appropriate for soundscape-specific assessment, the general PRS was retained because this experiment evaluated cross-modal restoration arising from combined auditory and olfactory cues in a simulated multisensory environment. The scale has demonstrated good reliability and validity and has been widely used to assess environmental restorativeness under multisensory conditions. Its 26 items comprise four a priori domains—Being-away (5 items), Fascination (8 items), Coherence (4 items), and Compatibility (9 items)—rated from 0 (not at all) to 6 (completely). To ensure accessibility and procedural consistency across groups, the Chinese items were read by the experimenter in a fixed order and neutral tone; participants responded verbally, and ratings were recorded without feedback or guidance. Within-domain principal component analyses were used only to generate standardised component scores, not to define the prespecified domain structure. The complete bilingual instrument and psychometric results are provided in Appendix D.

## 2.6 Physiological restoration measurements

Information on the physiological indicators was collected using a multi-channel physiological recording system (BIOPAC MP160). The recorded data were analysed using AcqKnowledge 5.0 software. Physiological signals were sampled at 2000 Hz. For each physiological indicator, the mean value over the 2-min stimulus-exposure period was calculated for each trial and used in subsequent analyses. The nine physiological indicators used for subsequent analysis included heart rate (HR), heart rate variability (HRV), the low-frequency (LF) and high-frequency (HF) components of the heart rate variability power spectrum, low frequency to high frequency ratio (LF/HF), R-wave amplitude ( $\Delta R$ ), respiration rate (RR), respiration depth (RD), and skin conductance level (SCL).

The physiological indicators selected in this study are relatively sensitive and have been shown to be effective in previous studies [28,42,56]. Cardiovascular responses, respiration, and skin conductance are all regulated by the autonomic nervous system [57]. The sympathetic and parasympathetic branches of the autonomic nervous system have generally opposing influences on

cardiac regulation: sympathetic activity is associated with physiological mobilisation and arousal, whereas parasympathetic activity, primarily through vagal regulation, supports rest and recovery [57,58]. Accordingly, increased sympathetic activity or decreased parasympathetic activity leads to an increase in HR, and vice versa [58,59].  $\Delta R$  reflects the amplitude of the electrocardiographic signal, which is related to blood pressure [60] and can be used as an indicator of emotional state. In general, increased stress is associated with reduced HRV [61]. HF is a broad marker of vagal modulation [62], and reduced vagal activity may accompany greater stress [61]. RR and RD are also associated with stress: increased perceived stress has been associated with higher respiratory frequency [63]. SCL is a physiological indicator reflecting sweat gland activity. Increased stress is associated with an increase in SCL [64]. In general, decreases in HR, RR, and SCL, and an increase in RD, are interpreted as indicating a more relaxing and comfortable environment.

Signal quality was evaluated separately for each indicator and trial. A trial-level value was coded as missing when signal loss, sensor detachment or contact failure, or severe movement artefacts prevented reliable extraction. Because electrocardiographic, respiratory, and electrodermal signals differ in their characteristics, no common numerical rejection threshold was applied across channels, and values were not excluded solely because they were statistically extreme.

## 2.7 Experimental procedure

The experiment was conducted in a semi-anechoic chamber at Ningbo University measuring  $5.2 \times 3.2 \times 2.7$  m (L  $\times$  W  $\times$  H), with a cut-off frequency of  $\leq 200$  Hz, background noise of  $\leq 20$  dBA, and an indoor temperature of  $26 \pm 1$  °C. The informed-consent form was read aloud to ensure that participants understood the study purpose and procedure. Physiological sensors were then attached to the participants: for electrocardiography measurement, the positive and negative electrodes were attached to the left and right wrists, respectively, and the ground electrode to the right ankle. For SCL measurement, electrodes were placed on the fingertips of the index and middle fingers of the non-dominant hand, and the respiratory belt was secured at the level of the xiphoid process. After the physiological sensors had been attached, participants

adjusted themselves to a comfortable seated position before the equipment was calibrated. A fixed point 45 cm from a participant's nose was then measured using a soft tape measure to determine the position of the beaker containing the odour stimulus during the experiment.

After the formal experiment commenced, participants were first instructed to relax fully for 10 minutes to allow resting-state physiological data to be recorded. Subsequently, seven sound-odour combinations were presented in a random order. The advance release time of each odour stimulus was strictly controlled according to the pilot experiment to ensure synchronisation of the auditory and olfactory stimuli. Each sound-odour combination was presented for 2 min, during which physiological responses were recorded. The exposure period was used to provide a sufficient observation window for physiological responses during soundscape exposure [56]. A 2-min inter-condition interval was then included before the next condition, during which the chamber was ventilated through an air duct connected to a fan at a ventilation rate of 8700 m<sup>3</sup> /h. Validation tests confirmed that the ventilation was sufficient to reduce residual odour concentrations to below the olfactory detection threshold. Participants' physiological indicators were recorded continuously during stimulus presentation, and the timing of stimulus transitions was marked using E-Prime. After the physiological measurement had been completed, participants rested for 10 minutes and then continued wearing the headphones and VR headset during the questionnaire session. The questionnaire session was allocated a longer duration because the items were read by the experimenter to ensure consistent administration across participants. All sound-odour combinations were then presented again in the same order to reproduce the conditions experienced by participants during the physiological measurement. Participants completed the questionnaire while experiencing each condition, and their responses were recorded by the experimenter. The experimental procedure and conditions are shown in Fig. 2.

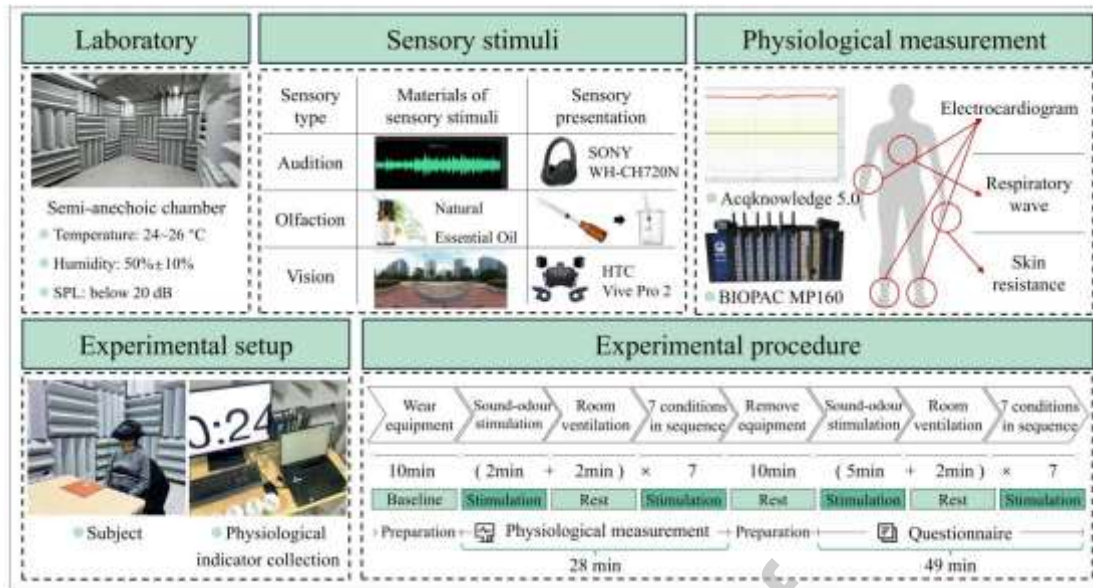


Fig. 2. Experimental procedure and conditions

## 2.8 Data analysis

Statistical analyses were conducted using IBM SPSS Statistics 27.0. For each a priori PRS domain—Being-away, Fascination, Coherence, and Compatibility—a separate one-component principal component analysis was conducted on the within-domain item correlation matrix without rotation. The resulting standardised first-component scores were approximately centred at zero and scaled to unit variance; negative values indicate scores below the overall sample mean. This procedure was used only to evaluate within-domain unidimensionality and generate standardised domain scores; it did not determine the number or conceptual structure of the PRS domains. Physiological outcomes were expressed as participant- and outcome-specific percentage changes from the resting baseline, with 1 representing a 1% increase. The complete analytical equations are provided in Appendix E.

First, paired-samples *t*-tests were used to analyse overall differences in psychological and physiological restoration between visually impaired and sighted participants. Valid trial-level observations were averaged within each participant, and paired differences were calculated as visually impaired minus sighted for the 36 prespecified stimulus-schedule-matched pairs, whose members received the same seven conditions in the same order. Two-sided tests, 95% confidence

intervals, and Cohen's  $d_z$  were reported; physiological analyses included only pairs with valid participant-level means for both members. Paired-difference normality was evaluated using the Shapiro-Wilk test, skewness, excess kurtosis, and standardised differences, with Wilcoxon signed-rank tests used as sensitivity analyses when departures were detected. These analyses estimated average differences between the two participant groups across comparable schedules rather than condition-specific Sound, Odour, or Sound×Odour effects.

Second, unified and group-specific linear mixed-effects models were used to analyse condition-specific effects and differences in response patterns between visually impaired and sighted participants. Unified models used all available trial-level observations from 76 participants and included Vision, Sound, Odour, all two-way interactions, and Vision×Sound×Odour as categorical fixed effects, with participant as a random intercept. Vision was a binary between-participant factor representing visual status (visually impaired versus sighted), not a manipulated visual-environment condition. The Vision×Sound, Vision×Odour, and Vision×Sound×Odour terms formally tested whether Sound and/or Odour response patterns differed between the two groups. Separate models for visually impaired and sighted participants included Sound, Odour, and Sound×Odour to characterise within-group patterns; significance in one group but not the other was not considered evidence of a between-group difference. Random slopes were not included because the limited number of repeated observations per participant did not support reliable estimation of more complex random-effect structures. Prespecified full and reduced models were fitted by maximum likelihood to identical outcome-specific observations and compared using likelihood-ratio tests [65]. Complete model equations and nested-model specifications are provided in Appendix E, and complete model outputs are provided in Appendix F.

Missing physiological values were not imputed; each model retained all available observations and permitted unequal realised cell sizes. Diagnostics included model convergence, conditional-residual skewness and excess kurtosis, standardised residuals, the association between absolute residuals and fitted values, and the random-intercept distribution. Absolute standardised residuals  $>3.29$  prompted observation- and participant-level influence refits for affected physiological models; statistical extremeness alone was not treated as evidence of measurement error or as grounds for exclusion from the primary analysis. Because the psychological domains

and physiological indicators represented theoretically distinct outcome variables, corrections were not applied across different outcome types. Paired tests were two-sided, and global inference used a nominal  $\alpha$  of 0.05. When global effects were decomposed using estimated marginal means (EMMs) from the full models, pairwise contrasts were Šidák-adjusted within the relevant Sound or Odour set; the 42 Sound×Odour cells were presented descriptively without cell-level significance tests. Cohen's  $d_z$  and semi-partial  $R^2$  were reported for paired comparisons and mixed-model fixed-effect comparisons, respectively. Diagnostics and sensitivity analyses, exact Vision- and outcome-specific cell sizes, and complete adjusted EMM results are provided in Appendices G, H, and I, respectively.

### 3 Results

#### 3.1 Differences in restoration between visually impaired and sighted individuals in sound-odour contexts

##### 3.1.1 Overall differences in psychological and physiological restoration

As a complementary analysis of overall group-level differences averaged across the assigned conditions, paired-samples t-tests were conducted within 36 prespecified stimulus-schedule-matched pairs. Table 1 and Fig. 3 therefore summarise overall participant-level differences averaged across the assigned conditions. Because recording or signal-processing failures prevented reliable extraction of some physiological indicators, complete-pair counts were outcome-specific: HR and LF,  $n = 34$ ; HRV, HF, LF/HF,  $\Delta R$ , and RR,  $n = 33$ ; RD,  $n = 32$ ; and SCL,  $n = 30$ .

**Table 1.** Overall participant-level differences in standardised PRS domain scores and physiological outcomes between visually impaired and sighted participants within stimulus-schedule-matched pairs

| Domain | Outcome | VI<br>(M±SD) | Sighted<br>(M±SD) | VI-Sighted | $t(df)$ | $p$ | Cohen's<br>$d_z$ |
|--------|---------|--------------|-------------------|------------|---------|-----|------------------|
|--------|---------|--------------|-------------------|------------|---------|-----|------------------|

|                                   |               |                |                |        |            |                    |        |
|-----------------------------------|---------------|----------------|----------------|--------|------------|--------------------|--------|
| Psychological restoration factors | Being-away    | 0.155 ± 0.525  | -0.169 ± 0.548 | 0.324  | 2.364 (35) | <b>0.024*</b>      | 0.394  |
|                                   | Fascination   | 0.283 ± 0.508  | -0.268 ± 0.626 | 0.55   | 4.122 (35) | <b>&lt;0.001**</b> | 0.687  |
|                                   | Coherence     | 0.174 ± 0.574  | -0.126 ± 0.716 | 0.299  | 2.061 (35) | <b>0.047*</b>      | 0.344  |
|                                   | Compatibility | 0.151 ± 0.638  | -0.157 ± 0.668 | 0.308  | 1.942 (35) | 0.06               | 0.324  |
| Physiological indicators          | HR            | 0.004 ± 0.028  | 0.003 ± 0.024  | 0.001  | 0.214 (33) | 0.832              | 0.037  |
|                                   | HRV           | 0.203 ± 0.342  | 0.014 ± 0.251  | 0.189  | 2.542 (32) | <b>0.016*</b>      | 0.442  |
|                                   | LF            | 0.164 ± 0.571  | 0.186 ± 0.375  | -0.022 | 0.185(33)  | 0.855              | -0.032 |
|                                   | HF            | 0.201 ± 0.730  | -0.004 ± 0.218 | 0.206  | 1.475 (32) | 0.15               | 0.257  |
|                                   | LF/HF         | 0.682 ± 1.549  | 0.481 ± 0.704  | 0.201  | 0.636 (32) | 0.53               | 0.111  |
|                                   | ΔR            | -0.007 ± 0.033 | -0.023 ± 0.042 | 0.016  | 2.035 (32) | 0.050              | 0.354  |
|                                   | RR            | -0.017 ± 0.077 | 0.018 ± 0.063  | -0.035 | 2.059(32)  | <b>0.048*</b>      | -0.358 |
|                                   | RD            | -0.043 ± 0.193 | -0.117 ± 0.266 | 0.073  | 1.260 (31) | 0.217              | 0.223  |
|                                   | SCL           | -0.137 ± 0.205 | -0.260 ± 0.251 | 0.123  | 1.910 (29) | 0.066              | 0.349  |

Note: HR = heart rate; HRV = heart rate variability; LF = low-frequency power of the HRV spectrum; HF = high-frequency power of the HRV spectrum; LF/HF = ratio of LF to HF power; ΔR = R-wave amplitude; RR = respiration rate; RD = respiration depth; SCL = skin conductance level. Reported *p* values are unadjusted outcome-specific values for the complementary paired comparisons. \* *p* < 0.05; \*\* *p* < 0.01.

The paired comparisons detected higher participant-level PRS component scores among visually impaired participants for Being-away (*p* = 0.024, Cohen's *d<sub>z</sub>* = 0.394), Fascination (*p* < 0.001, Cohen's *d<sub>z</sub>* = 0.687), and Coherence (*p* = 0.047, Cohen's *d<sub>z</sub>* = 0.344), with the largest difference observed for Fascination. Compatibility did not reach the nominal significance threshold (*p* = 0.060, Cohen's *d<sub>z</sub>* = 0.324), indicating no reliable overall group difference in perceived person-environment fit and support for intended activities. Among the physiological outcomes, visually impaired participants showed higher HRV (*p* = 0.016, Cohen's *d<sub>z</sub>* = 0.442) and lower RR (*p* = 0.048, Cohen's *d<sub>z</sub>* = -0.358), whereas no statistically significant paired differences were detected for the remaining indicators. Thus, overall physiological differences were limited and outcome-specific rather than consistent across indicators. These *p* values are unadjusted outcome-specific results from the complementary paired comparisons and are interpreted separately rather than as evidence for a domain-wide effect.

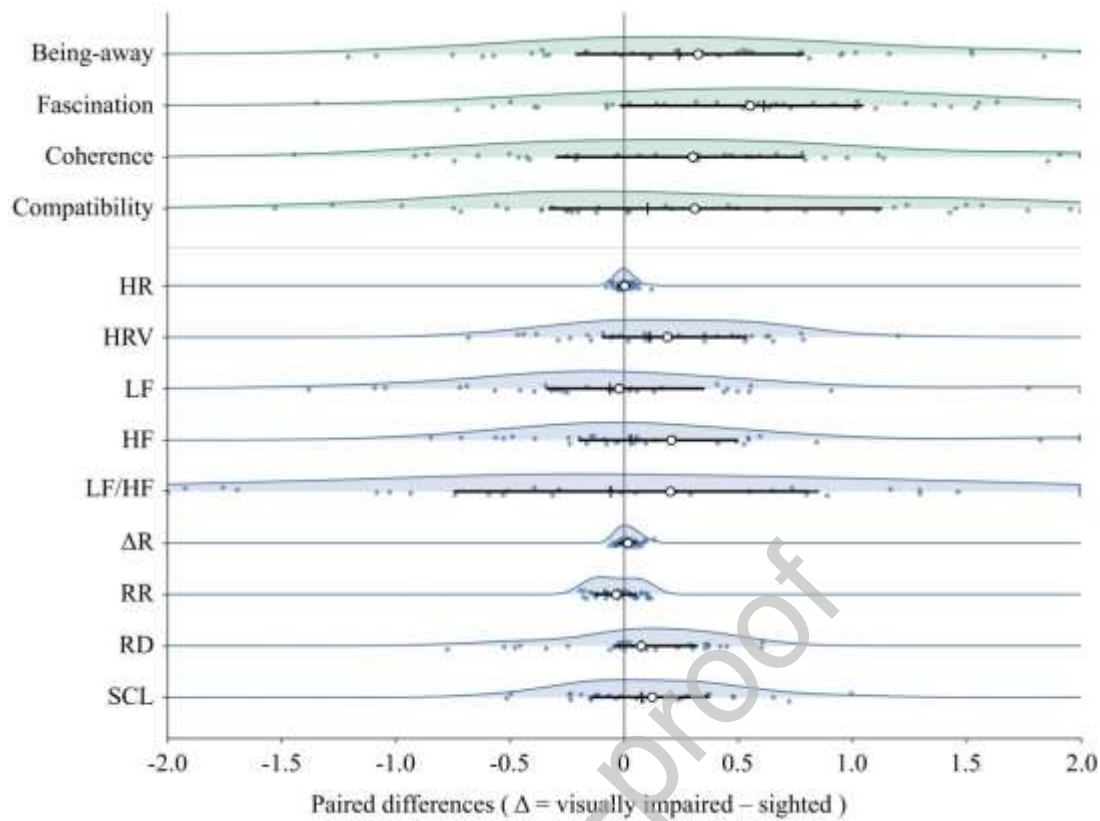


**Fig. 3.** Distributions of participant-level paired differences within stimulus-schedule-matched pairs

Fig. 3 visualises the distributions, central tendencies, and 95% confidence intervals of the participant-level paired differences underlying Table 1. Shaded half-violins show the kernel-density estimates; small filled points represent individual paired differences; open circles represent means; short vertical ticks indicate medians; and bold horizontal lines represent interquartile ranges (25th – 75th percentiles). The vertical reference line at  $\Delta = 0$  indicates no between-group difference. The psychological-restoration outcomes showed an overall positive shift, with the distributions for Being-away, Fascination, and Coherence predominantly favouring visually impaired participants. In contrast, most physiological paired differences were more widely distributed around the zero reference line, indicating substantial between-pair variation and limited overall group differences. HRV showed a positive shift and RR a negative shift, consistent with the statistically significant paired comparisons reported in Table 1. Although graphical deviations

from zero were also apparent for some other indicators, including RD and LF/HF, their paired comparisons were not statistically significant. Observations separated from the main distributions were not automatically treated as invalid. Formal diagnostics identified one extreme paired difference for LF/HF, but its exclusion did not change the nonsignificant conclusion,  $t(31) = -0.019, p = .985$ . Overall, the paired analysis indicated higher psychological restoration among visually impaired participants, whereas physiological differences were limited and outcome-specific, primarily involving HRV and RR. However, this condition-marginal analysis could not determine whether the limited overall physiological differences concealed condition-specific response patterns; these were therefore examined subsequently using trial-level mixed-effects models.

### 3.1.2 Between-group differences in sound-odour response patterns: unified mixed-effects models

To formally test whether the effects of sound and odour differed between visually impaired and sighted participants, all available trial-level observations for each outcome were analysed using unified linear mixed-effects models. Vision (visual status), Sound, Odour, and their interactions were included as fixed effects, with participant ID included as a random intercept. Accordingly, the Vision×Sound, Vision×Odour, and Vision×Sound×Odour terms represented the formal between-group tests of differential responses to Sound and/or Odour. Fixed-effect significance was evaluated using prespecified likelihood-ratio comparisons of nested models fitted by maximum likelihood to the same observations, as detailed in Section 2.8 and Appendix E. Table 2 summarises the Vision interaction tests and ICCs, and complete model outputs and semi-partial  $R^2$  values are reported in Table F1.

**Table 2.** Unified mixed-effects-model tests of between-group differences in sound and odour response patterns

| Indicators | $p$ (Vision×Sound) | $p$ (Vision×Odour) | $p$ (Vision×Sound×Odour) | ICC   |
|------------|--------------------|--------------------|--------------------------|-------|
| Being-away | 0.349              | 0.723              | 0.525                    | 0.283 |

|               |              |                  |                  |       |
|---------------|--------------|------------------|------------------|-------|
| Fascination   | 0.116        | 0.148            | 0.758            | 0.314 |
| Coherence     | 0.833        | 0.777            | 0.549            | 0.383 |
| Compatibility | 0.098        | 0.383            | 0.667            | 0.436 |
| HR            | 0.128        | 0.114            | <b>&lt;0.001</b> | 0.467 |
| HRV           | <b>0.049</b> | 0.064            | 0.244            | 0.343 |
| LF            | <b>0.025</b> | <b>&lt;0.001</b> | 0.526            | 0.533 |
| HF            | <b>0.006</b> | <b>0.036</b>     | 0.103            | 0.666 |
| LF/HF         | <b>0.016</b> | <b>0.006</b>     | 0.785            | 0.500 |
| $\Delta R$    | 0.886        | 0.708            | 0.862            | 0.636 |
| RR            | 0.699        | 0.435            | 0.359            | 0.449 |
| RD            | 0.388        | <b>0.010</b>     | 0.207            | 0.411 |
| SCL           | 0.304        | 0.377            | 0.870            | 0.565 |

Note: Vision denotes participant visual status (visually impaired versus sighted). Reported  $p$  values are unadjusted outcome-specific likelihood-ratio tests of the prespecified global interaction terms. \*  $p < 0.05$ ; \*\*  $p < 0.01$ .

None of the Vision $\times$ Sound, Vision $\times$ Odour, or Vision $\times$ Sound $\times$ Odour interactions was statistically significant for Being-away, Fascination, Coherence, or Compatibility. Thus, although the paired comparisons in Section 3.1.1 identified overall differences between visually impaired and sighted participants for several psychological-restoration outcomes, the unified models provided no evidence that the Sound, Odour, or Sound $\times$ Odour response patterns differed systematically by Vision. The paired results are therefore more consistent with overall level shifts than with moderation of the experimental-condition effects: visually impaired participants tended to report higher overall psychological restoration, while visually impaired and sighted participants exhibited broadly similar psychological response patterns across the sound and odour conditions.

Among the physiological outcomes, statistically significant Vision interactions were detected for HR, HRV, LF, HF, LF/HF, and RD. The largest interaction was the Vision $\times$ Sound $\times$ Odour effect for HR ( $p < 0.001$ , semi-partial  $R^2 = 0.089$ ). Significant Vision $\times$ Sound interactions were also observed for HRV, LF, HF and LF/HF, whereas significant Vision $\times$ Odour interactions were found for LF, HF, LF/HF and RD. All of these significant two-way interactions had relatively small effect sizes (semi-partial  $R^2 = 0.010 - 0.025$ ). Among the significant Vision $\times$ Sound interactions, those for HRV and LF/HF were sensitive to participant-level influence analyses and are therefore interpreted cautiously. Overall, unlike the broadly parallel psychological response patterns, the physiological responses of visually impaired and sighted participants differed for

selected cardiovascular, autonomic, and respiratory indicators. However, these differences were indicator-specific and generally small rather than reflecting a consistent tendency for one group to show stronger physiological restoration. The subsequent group-specific models and EMMs were therefore used to determine how the Sound, Odour, and Sound×Odour response patterns were expressed within visually impaired and sighted participants separately; significance in only one group was not treated as formal evidence of a between-group difference.

### 3.2 Comparison of sound and odour effects on psychological restoration between visually impaired and sighted individuals

Following the formal between-group tests in the unified models, separate random-intercept linear mixed-effects models were fitted for visually impaired and sighted participants to characterise the within-group effects of Sound, Odour, and Sound×Odour on each of the four psychological-restoration outcomes. The omnibus fixed-effect contributions were evaluated using likelihood-ratio tests. These models were used to characterise within-group response patterns, whereas formal between-group differences were assessed using the Vision interaction terms in the unified models. Table 3 summarises the omnibus tests and ICCs, and complete model outputs are reported in Table F2.

**Table 3.** Comparison of mixed-effects models of sound and odour on psychological restoration between visually impaired and sighted individuals

| Indicator     | Vision  | <i>p</i> (Sound) | <i>p</i> (Odour) | <i>p</i> (Sound×Odour) | ICC   |
|---------------|---------|------------------|------------------|------------------------|-------|
| Being-away    | VI      | <0.001           | 0.392            | 0.370                  | 0.272 |
|               | Sighted | <0.001           | 0.436            | 0.697                  | 0.292 |
| Fascination   | VI      | 0.002            | 0.447            | 0.269                  | 0.297 |
|               | Sighted | <0.001           | 0.279            | 0.796                  | 0.326 |
| Coherence     | VI      | 0.003            | 0.682            | 0.602                  | 0.278 |
|               | Sighted | <0.001           | 0.541            | 0.395                  | 0.477 |
| Compatibility | VI      | <0.001           | 0.136            | 0.058                  | 0.501 |
|               | Sighted | <0.001           | 0.280            | 0.487                  | 0.387 |

Note: Vision denotes participant visual status (visually impaired versus sighted). Reported *p* values are unadjusted outcome-specific likelihood-ratio tests of the prespecified global interaction terms. \* *p* < 0.05; \*\* *p* < 0.01.

Table 3 indicates broadly consistent psychological-restoration patterns in the two groups. Statistically significant omnibus Sound effects were detected for Being-away, Fascination, Coherence, and Compatibility in both visually impaired and sighted participants. These effects were moderate in magnitude, with semi-partial  $R^2$  values ranging from 0.181 to 0.221 in the visually impaired group and from 0.174 to 0.234 in the sighted group. In contrast, no statistically significant omnibus Odour effect or Sound×Odour interaction was detected for any psychological outcome in either group. The Sound×Odour interaction for Compatibility in the visually impaired group approached, but did not reach, the nominal significance threshold ( $p = 0.058$ ). Thus, within both groups, psychological restoration varied consistently across Sound conditions, whereas Odour and Sound×Odour did not show stable effects under the present experimental conditions. The ICCs ranged from approximately 0.27 to 0.50, indicating moderate within-participant clustering, with relatively higher clustering for Compatibility in visually impaired participants and Coherence in sighted participants.

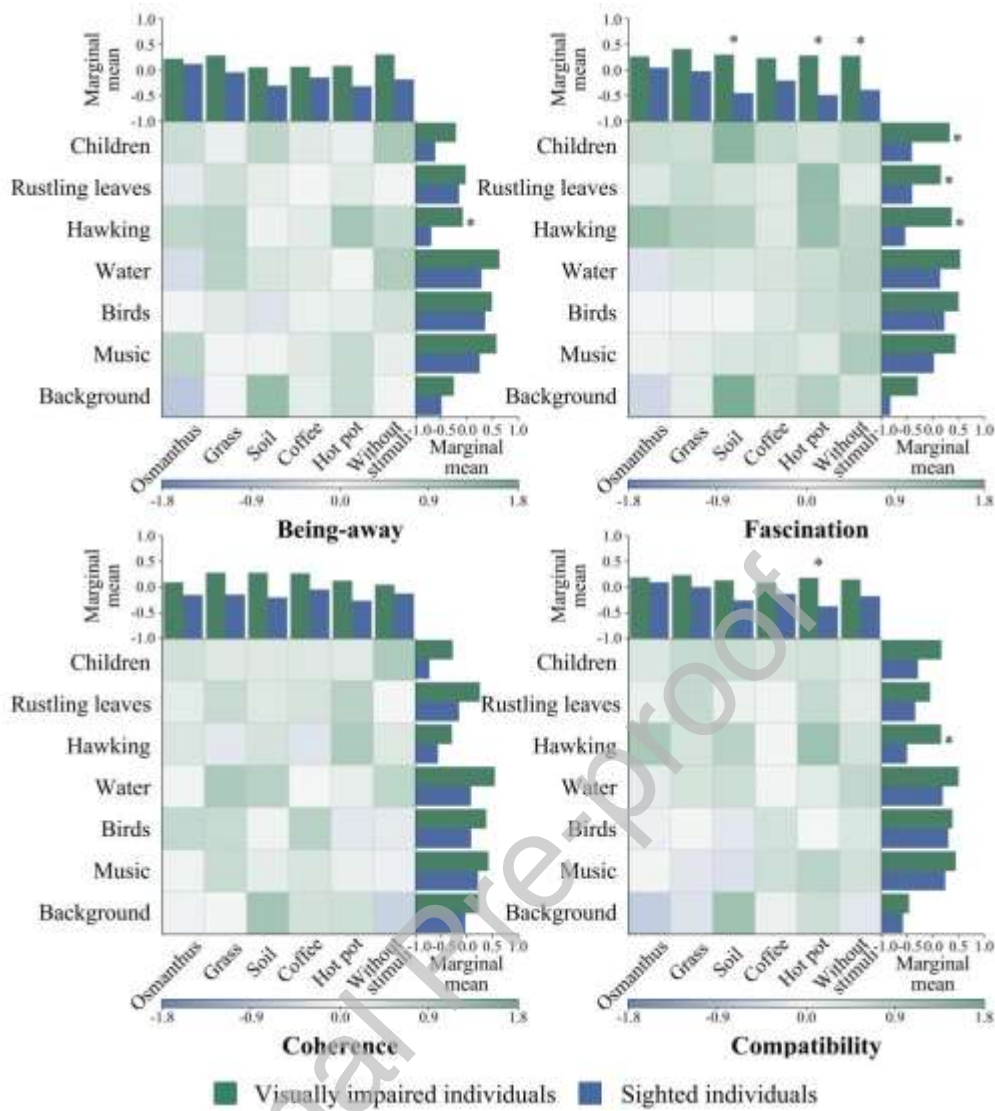


**Fig. 4.** Psychological restoration differences between visually impaired and sighted individuals under sound, odour, and combined sound-odour conditions (difference = visually impaired – sighted)

Fig. 4 presents the model-estimated psychological-restoration patterns across the Sound, Odour, and Sound×Odour conditions. All 42 Sound×Odour combinations were represented in both groups. For the psychological outcomes, realised cell sizes ranged from 5 to 8 observations in the visually impaired group and from 5 to 10 in the sighted group; exact cell sizes are reported in Appendix H. Statistical inference regarding the overall effects of Sound, Odour, and Sound×Odour was based on the likelihood-ratio tests reported in Table 3. The cell-specific EMMs

and 95% confidence intervals visualise the fitted Sound×Odour patterns and were not interpreted as separately tested differences between individual cells. Asterisks are restricted to the Šidák-adjusted between-group marginal contrasts displayed alongside the grids and do not indicate omnibus Sound or Odour effects. Complete EMMs, 95% confidence intervals, and adjusted contrasts are reported in Table II.

The fitted EMM profiles generally placed sounds of water, birds, and music among the higher psychological-restoration levels across the four outcomes in both groups, whereas background sound tended to occupy the lower range. Hawking and children's sounds, both of which can signal identifiable everyday activities in public spaces, showed clearer between-group differences. After Šidák adjustment, visually impaired participants had higher marginal EMMs than sighted participants for hawking sound in Being-away, Fascination, and Compatibility, and for sounds of children and rustling leaves in Fascination. Additional adjusted differences favouring visually impaired participants were detected for Fascination under soil odour, hotpot odour, and without-stimuli conditions, and for Compatibility under the hotpot odour condition. These findings represent between-group contrasts at specific Sound or Odour levels rather than statistically tested differences between individual Sound×Odour cells. Although some variation was visible across Odour levels and individual combinations, Table 3 detected no statistically significant omnibus Odour effect or Sound×Odour interaction for any psychological outcome in either group. The corresponding cell-level patterns should therefore be interpreted descriptively, particularly given the limited cell-specific sample sizes.

Overall, visually impaired and sighted participants showed broadly similar psychological-restoration patterns across the experimental conditions. Sound was the more consistent source of variation in both groups, with sounds of water, birds, and music generally associated with higher fitted restoration scores. Nevertheless, the adjusted marginal contrasts indicated that visually impaired participants had more favourable responses than sighted participants to hawking and children's sounds, which can signal identifiable everyday activities, in specific restoration domains. By contrast, Odour and Sound×Odour did not demonstrate stable omnibus effects, and isolated differences between grid cells should not be interpreted inferentially.

### 3.3 Comparison of sound and odour effects on physiological restoration between visually impaired and sighted individuals

The physiological analysis followed the same group-specific approach as the psychological analysis. Separate random-intercept linear mixed-effects models were fitted for visually impaired and sighted participants to characterise the within-group effects of Sound, Odour, and Sound×Odour on each physiological outcome. Table 4 summarises the omnibus tests and ICCs, and complete model outputs are reported in Table F3.

**Table 4.** Comparison of mixed-effects models of sound and odour on physiological restoration between visually impaired and sighted individuals

| Indicator | Vision  | <i>p</i> (Sound) | <i>p</i> (Odour) | <i>p</i> (Sound×Odour) | ICC   |
|-----------|---------|------------------|------------------|------------------------|-------|
| HR        | VI      | 0.134            | 0.091            | 0.098                  | 0.654 |
|           | Sighted | <b>&lt;0.001</b> | <b>&lt;0.001</b> | <b>&lt;0.001</b>       | 0.262 |
| HRV       | VI      | 0.319            | 0.188            | 0.389                  | 0.295 |
|           | Sighted | 0.397            | 0.812            | 0.788                  | 0.376 |
| LF        | VI      | 0.332            | 0.194            | 0.522                  | 0.594 |
|           | Sighted | 0.215            | 0.084            | 0.421                  | 0.470 |
| HF        | VI      | <b>0.027</b>     | 0.134            | 0.147                  | 0.695 |
|           | Sighted | 0.434            | 0.209            | 0.753                  | 0.451 |
| LF/HF     | VI      | 0.308            | 0.332            | 0.376                  | 0.604 |
|           | Sighted | 0.137            | 0.236            | 0.607                  | 0.283 |
| ΔR        | VI      | 0.460            | 0.195            | 0.249                  | 0.621 |
|           | Sighted | 0.423            | 0.458            | 0.299                  | 0.648 |
| RR        | VI      | 0.279            | 0.295            | 0.162                  | 0.507 |
|           | Sighted | 0.733            | 0.915            | 0.885                  | 0.387 |
| RD        | VI      | 0.341            | 0.222            | 0.196                  | 0.354 |
|           | Sighted | 0.292            | <b>0.013</b>     | 0.314                  | 0.445 |
| SCL       | VI      | 0.074            | 0.258            | 0.412                  | 0.589 |
|           | Sighted | 0.895            | 0.830            | 0.718                  | 0.554 |

Note: Vision denotes participant visual status (visually impaired versus sighted). Reported *p* values are unadjusted outcome-specific likelihood-ratio tests of the prespecified global interaction terms. \* *p* < 0.05; \*\* *p* < 0.01.

Table 4 shows that the within-group physiological effects were relatively sparse and outcome-specific. In visually impaired participants, the full-data model detected an omnibus

Sound effect for HF ( $p = 0.027$ , semi-partial  $R^2 = 0.103$ ), suggesting possible sound-related variation in parasympathetic activity. However, this result was sensitive to participant-level influence analysis and is therefore treated as exploratory rather than as evidence of a stable group-specific effect. No statistically significant Sound, Odour, or Sound×Odour effect was detected for the remaining physiological outcomes in this group. In sighted participants, HR showed statistically significant omnibus effects of Sound, Odour, and Sound×Odour (all  $p < 0.001$ ; semi-partial  $R^2 = 0.243$ – $0.302$ ), while RD showed a significant Odour effect ( $p = 0.013$ , semi-partial  $R^2 = 0.165$ ). No statistically significant effect was detected for the remaining physiological outcomes. The ICCs ranged from 0.262 to 0.695, indicating moderate-to-high within-participant clustering. Overall, physiological modulation was concentrated in selected indicators rather than consistently expressed across outcomes: visually impaired participants showed a tentative sound-related response in HF, whereas sighted participants showed clearer condition-related variation in HR and odour-related variation in RD.

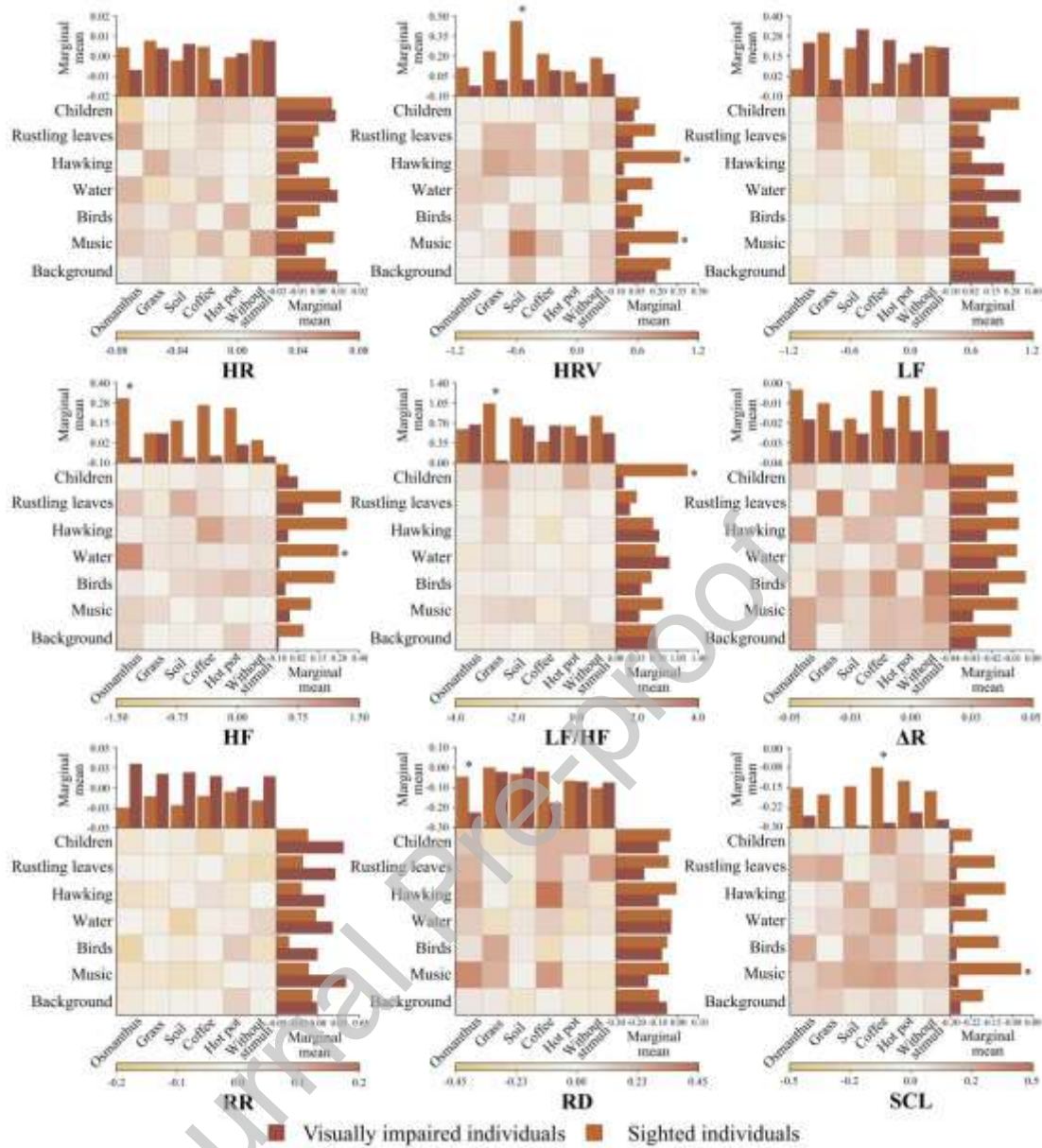


**Fig. 5.** Physiological restoration differences between visually impaired and sighted individuals under sound, odour, and combined sound-odour conditions (difference = visually impaired – sighted)

Fig. 5 uses the same graphical and inferential conventions as Fig. 4 to present the model-estimated physiological responses. Because the availability of physiological measurements varied by outcome, the valid sample sizes of individual Sound  $\times$  Odour cells were not identical; complete group- and outcome-specific cell sizes are reported in Appendix H. The central heat maps display

the fitted between-group differences for the 42 Sound  $\times$  Odour combinations descriptively, whereas the asterisks in the upper and right marginal plots indicate only Šidák-adjusted between-group contrasts at particular Odour or Sound levels. The complete EMMs, 95% confidence intervals, between-group differences, and adjusted  $p$  values underlying Fig. 5 are reported in Appendix I.

Visually impaired participants had higher HRV estimates under soil odour (VI – sighted:  $\Delta\text{EMM} = 0.438$ , adjusted  $p = 0.001$ ), hawking sound ( $\Delta\text{EMM} = 0.410$ , adjusted  $p = 0.004$ ), and music ( $\Delta\text{EMM} = 0.355$ , adjusted  $p = 0.005$ ). Higher estimates for visually impaired participants were also detected for HF under osmanthus odour ( $\Delta\text{EMM} = 0.371$ , adjusted  $p = 0.026$ ) and water sound ( $\Delta\text{EMM} = 0.355$ , adjusted  $p = 0.050$ ); for LF/HF under grass odour ( $\Delta\text{EMM} = 0.990$ , adjusted  $p = 0.011$ ) and children's sound ( $\Delta\text{EMM} = 1.083$ , adjusted  $p = 0.008$ ); and for RD under osmanthus odour ( $\Delta\text{EMM} = 0.177$ , adjusted  $p = 0.031$ ). For SCL, the visually impaired group showed less negative fitted changes than the sighted group under coffee odour ( $\Delta\text{EMM} = 0.208$ , adjusted  $p = 0.011$ ) and music ( $\Delta\text{EMM} = 0.228$ , adjusted  $p = 0.006$ ). No Šidák-adjusted marginal between-group contrast was detected for HR, LF,  $\Delta\text{R}$ , or RR.

Fig. 5 describes different aspects of the physiological responses. For example, HR and LF showed statistically significant Vision interactions but no adjusted marginal contrast at any individual Sound or Odour level. Their between-group differences may therefore have involved combination-specific or compensating response patterns that were attenuated when averaged across the other factor. Conversely, the adjusted SCL contrasts under coffee odour and music occurred without a statistically significant Vision interaction and thus represent localised group differences rather than systematic between-group differences in the overall Sound or Odour response pattern. The physiological meaning of the direction of these contrasts also differed by indicator. Higher HRV and HF values may be compatible with greater parasympathetic activity, whereas higher LF/HF values and the less negative SCL changes observed in the visually impaired group cannot be interpreted in the same way. Consequently, the results do not indicate that either group consistently experienced greater physiological restoration. Instead, the between-group differences were dependent on the physiological indicator, stimulus level, and form of statistical comparison.

## 4 Discussion

### 4.1 Divergence between psychological and physiological restoration: different response pathways of visually impaired and sighted individuals in auditory-olfactory environments

An important finding of this study is that the differences between visually impaired and sighted individuals in auditory-olfactory environments did not emerge simultaneously at the psychological and physiological restoration levels. Visually impaired individuals experienced higher overall psychological restoration, and in the within-group models, all four psychological restoration factors in both groups were consistently influenced by the main effect of sound. In contrast, the physiological results were more fragmented and indicator-specific. In the combined analysis, sound, odour, and their interactions influenced only a small number of physiological indicators, suggesting that short laboratory exposure produced clearer psychological appraisal than uniform autonomic changes. The separate group analyses showed clearer but different patterns: the visually impaired group mainly showed sound effects in HF, whereas the sighted group showed effects of sound, odour, or their interaction in indicators such as HR and RD. This difference indicates group-specific physiological responses that may be partly obscured when the two groups are analysed together, rather than a contradiction between analyses. These findings suggest that the differences between the two groups cannot be understood simply in terms of one group being more restored than the other. The apparent difference between the paired comparisons and mixed-effects models reflects their distinct analytical purposes. The paired comparisons assessed overall group differences averaged across matched conditions, whereas the Vision interaction terms examined whether Sound and Odour response patterns differed between groups. Thus, a consistent elevation in one group across conditions can produce an overall difference without significant Vision  $\times$  Sound, Vision  $\times$  Odour, or Vision  $\times$  Sound  $\times$  Odour interactions. These findings indicate higher overall restoration in selected outcomes among visually impaired participants, but no evidence of systematic divergence in their relative Sound and Odour response patterns. Non-significant interactions should not be interpreted as evidence of equivalence. Rather,

restoration may be reflected in different psychological and physiological response patterns. This pattern is consistent with the fundamental premise of restoration theory, which holds that restoration involves multiple dimensions including cognitive, emotional, and physiological regulation, and that psychological evaluations and physiological responses are not necessarily expected to occur in complete synchrony. Previous soundscape studies have similarly shown that subjective perception and physiological indicators often exhibit complementary rather than overlapping relationships [66,67]. An additional methodological consideration is the two-minute exposure duration. This short window may have limited the emergence or stabilisation of slower autonomic responses, contributing to the indicator-specific physiological findings. However, because duration was fixed rather than experimentally varied, this explanation remains tentative.

For visually impaired individuals, the results showed a relatively consistent psychological restorative pattern, but more heterogeneous physiological responses across indicators. This may indicate that non-visual cues contribute to restorative appraisal by improving the perceived comprehensibility, predictability, and safety of the environment, while these appraisals are not necessarily translated into uniform changes across all physiological indicators. Interview evidence indicated that visually impaired individuals were more likely to experience restoration from natural environments only when they felt safe [38]. Similarly, other studies reported that visually impaired individuals particularly emphasised clarity, comfort, and safety when evaluating urban sound environments [36]. Furthermore, research on mobility strategies among people with visual impairment has confirmed the important role of auditory cues in orientation and information support in unfamiliar environments [68]. Therefore, the higher psychological restoration associated with certain sounds should not be interpreted only in terms of general pleasantness. It may also be understood in relation to the contextual information provided by these sounds, such as cues about environmental predictability, accessibility, and the presence of surrounding activities. Such an interpretation may help explain why stronger psychological restoration among visually impaired individuals was not necessarily accompanied by consistent changes in the same direction across all autonomic physiological indicators.

The olfactory findings further support this interpretation. Current evidence does not support the simple assumption that visually impaired individuals have generally superior olfactory

abilities. Instead, a systematic review and meta-analysis showed that the overall differences between blind and sighted individuals in olfactory threshold, discrimination, and identification were not consistent [69]. Therefore, the differences between visually impaired and sighted individuals in the effects of odour observed in this study are better understood as differences in cue weighting than in sensory ability. A study on park environments similarly suggested that visually impaired individuals may be more sensitive to certain odours, but that this sensitivity is more likely to reflect contextual use of information rather than a stable subjective main effect [45].

Based on these findings, the incomplete correspondence between psychological and physiological responses can be interpreted as a form of partial decoupling: psychological restoration may primarily reflect participants' integrated appraisal of environmental meaning, safety, and comprehensibility, whereas physiological restoration reflects more immediate autonomic changes that are also more susceptible to individual regulatory pathways. Future research could further establish coupling models between psychological restoration factors and indicators such as HF, RR, and SCL, while incorporating variables such as safety, clarity, and orientation confidence into mediating pathways. It would also be valuable to distinguish between congenitally blind, adventitiously blind, and low-vision groups to more directly test whether different populations indeed exhibit a pattern of similar outcomes through different pathways in restorative processes.

#### **4.2 Sound-type differences: contextual value of sounds signalling identifiable everyday activities for visually impaired individuals**

The present findings are consistent with the soundscape view that acoustic environments are perceived and understood by people in context [70]. Under controlled SPL conditions, restorative responses differed by sound-source type and meaning. Natural sounds were associated with stronger perceived restorativeness in both groups, while the visually impaired group also showed relatively positive responses to sounds signalling identifiable everyday activities, particularly hawking and children's sounds. These results suggest that sound-source meaning may shape

restoration in auditory-olfactory environments involving visually impaired and sighted participants.

The relatively favourable responses of visually impaired participants to children's and hawking sounds were consistent with the preliminary interviews, in which these sounds were linked to vitality, everyday social activity, and a lively public-space atmosphere, suggesting a possible safety-certainty mechanism. For many visually impaired individuals, audition provides primary access to situational awareness; thus, sounds signalling identifiable everyday activities may reduce ambiguity about what is happening nearby, which can increase perceived controllability and comfort. Urban evidence specific to visually impaired populations supports this interpretation: visually impaired individuals' evaluations of urban sound environments emphasise safety, clarity, and avoidance of traffic-related cues, and their comfort can be closely related to how understandable and predictable the soundscape feels [35,36].

A second mechanism is functional: sounds signalling identifiable everyday activities can operate as auditory landmarks supporting orientation and wayfinding. A comprehensive review of cognitive map formation in blindness highlights that people with blindness can build cognitive maps using non-visual modalities and that multimodal information can be more effective than single-modality cues [71]. In public spaces, sources like a playground (sound of children) or street vending (sound of hawking) can be relatively stable in location and meaning, providing repeated, recognisable anchors that support route representations and reduce navigational uncertainty. When such anchoring reduces vigilance demands, physiological restoration may improve—even if the sound is eventful.

### **4.3 Commonalities in restoration: universal value of auditory-olfactory environments**

Despite group-specific sensory weighting, the results also show strong commonalities: auditory main effects on psychological restoration were stable and significant in both groups, and natural sounds (e.g., water, birds) consistently produced stronger restorative experiences. These convergences support the proposition that public spaces can adopt auditory-first restorative design

principles that benefit diverse users, consistent with classic restoration theories emphasising attention recovery and stress reduction in benign natural environments [13,72].

Odour showed weaker and less consistent effects than sound in the present study, especially for psychological restoration. Both auditory and olfactory cues can convey information about identifiable events or activities; for example, coffee and hotpot odours can be strongly associated with particular urban activities. Therefore, the weaker odour effects observed here should not be attributed simply to lower identifiability or event-relatedness. Instead, they may reflect differences in cue salience and temporal characteristics, as well as the greater dependence of olfactory effects on congruence, masking, and specific sound-odour combinations [20,46,49].

A key implication for universality is thus not that multisensory always outperforms unisensory, but that auditory-olfactory environments provide a scalable toolkit. In other words, soundscapes may offer a more reliable restorative baseline, whereas smellscapes may act as context-sensitive elements that adjust or enhance the sensory atmosphere of specific spaces. In addition, for visually impaired users, auditory and olfactory interventions should also be coordinated with tactile features that support orientation, wayfinding, and safe mobility [73]. Such an integrated multisensory approach may help public spaces support both restorative experience and everyday usability.

#### **4.4 Limitations and implications for future studies**

This study examined the effects of auditory-olfactory interactions on restorative responses in visually impaired and sighted individuals in urban public spaces. As with any research, several limitations should be acknowledged. First, preliminary interviews for stimulus selection involved only visually impaired individuals, consistent with the aim of identifying auditory and olfactory cues that they themselves considered restorative; however, this may have made the selected stimuli more closely aligned with their experiences than with those of sighted participants. Future studies could compare stimuli selected by both groups. Second, the same VR visual scene controlled the external visual context, but the study did not directly measure participants' perceived visual information. Thus, the influence of individual differences in visual perception on cross-group comparisons could not be fully separated. Moreover, a single constant visual scene

could not fully reflect the variability and site-specific congruence of multisensory cues in real urban public spaces. Future studies could include visual-perception measures or use ecologically matched multisensory scenarios. Third, SPL and odour concentration were fixed at moderate levels, limiting the examination of intensity-dependent effects. Although SPL was standardised, loudness differed across sounds and subjective loudness was not assessed, which may have influenced the observed sound-type effects. Future studies should examine multiple intensity levels and include subjective loudness ratings. Fourth, although the two-minute exposure was standardised across scenarios, it may have provided a limited window for slower physiological responses to emerge or stabilise. Future studies should compare multiple exposure durations and examine response trajectories during exposure and recovery. Finally, the laboratory-based VR setting differed from real urban public spaces, and the cumulative duration of wearing the VR headset may have caused fatigue or reduced attention in later scenarios. Future studies could combine field experiments or augmented reality simulations with shorter blocks, scheduled breaks, and fatigue assessments.

## 5 Conclusions

This study compared psychological and physiological restoration in visually impaired and sighted participants under 42 Sound  $\times$  Odour combinations in simulated urban public spaces. The analytical framework distinguished overall group-level differences from differences in condition-response patterns.

Paired comparisons showed higher Being-away, Fascination, and Coherence scores among visually impaired participants. They also showed higher HRV and lower RR, but no consistent physiological advantage was observed across the remaining indicators. The mixed-effects models detected no Vision interactions for the psychological outcomes. Thus, the two groups differed in their overall levels of selected psychological outcomes while showing broadly similar relative response patterns across Sound and Odour conditions.

Sound significantly affected all four psychological outcomes in both groups. By contrast, Odour and Sound  $\times$  Odour showed no stable omnibus effects. Water, birds, and music were

generally associated with higher psychological-restoration scores. Visually impaired participants also showed more favourable responses to sounds signalling identifiable everyday activities, specifically hawking and children's sounds, in specific restoration domains.

Physiological effects were sparse and indicator-specific. Selected Vision interactions were detected, but most two-way effects were small and some were influence-sensitive. The visually impaired group showed a tentative Sound effect in HF, whereas the sighted group showed clearer condition-related variation in HR and an Odour effect in RD. Neither group consistently exhibited greater physiological restoration.

These findings support auditory-led multisensory design in inclusive urban public spaces. Natural sounds may provide broadly restorative cues, while sounds signalling identifiable everyday activities may offer additional contextual value for visually impaired users. Under the present conditions, odour is better treated as a context-sensitive modifier than as a consistently independent driver of restoration.

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## Declaration of competing interests

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.

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#### Declaration of interests

☒ 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.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: