

Article

The Impact of Blue–Green Visual Composition in Waterfront Walkway on Psychophysiological Recovery: Evidence from First-Person Dynamic VR Exposure and Semantic Segmentation Quantification

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Abstract

Urban waterfront walkways are everyday public built environments where people commonly engage in slow walking, yet evidence remains limited that links what pedestrians see to immediate psychophysiological responses under controlled first-person dynamic exposure. To address this gap, we developed a fixed-speed, fixed-duration VR walk-through model using real-world 360° panoramic video and quantified scene visual composition via computer vision-based image analysis. Based on the visible shares of key components (greenery, water, sky, hardscape, and built structures), clips were grouped into four interpretable waterfront typologies: Vegetation-Enclosed, Built-Dominant, Hardscape-Plaza, and Blue-Open. Fifty healthy adults completed within-subject VR exposures to the four typologies (50 s per clip), while multimodal physiological signals and brief affect and landscape ratings were collected before and after exposure. The results showed that scenes with more water and vegetation coverage, along with expansive views, were associated with promoted autonomic nervous system calming responses, whereas scenes with fewer natural elements and higher built structure density were more likely to induce tension responses. Negative emotions decreased significantly across all four scene experiences, though artificial scenes concurrently exhibited emotional improvement alongside physiological tension. Overall, brief first-person dynamic VR exposure can yield immediate emotional benefits, and waterfront designs combining water proximity, abundant greenery, and expansive vistas may maximize short-term restorative potential, offering quantitative targets for health-supportive planning and retrofitting.

Keywords: virtual reality; waterfront walkway; dynamic walking exposure; built–natural interface design; physical and psychological health



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1. Introduction

As urbanization intensifies and daily routines accelerate, stress-related health burdens have become more visible, increasing interest in low-cost, scalable built-environment and nature-based interventions that can be inexpensive and scalable in everyday settings [1–4]. Evidence links exposure to urban green space with lower depression and anxiety and with better mood and psychological well-being [4–7]. Beyond greenery alone, waterfront landscapes incorporating ‘blue elements’ are recognized as possessing significant potential

for reducing psychological fatigue and enhancing mood due to their unique environmental appeal. These settings offer more diverse sensory stimulation and higher levels of enjoyment [8–10]. Accordingly, blue–green integrated waterfront landscapes are becoming a key focus of environmental health practice [11]. Waterfront walkways are not only natural landscapes, but also linear public spaces embedded in the urban built environment, whose spatial design affects daily walking experience and health.

There is substantial evidence supporting the restorative effects of natural exposure on both physical and mental well-being. Stress Recovery Theory (SRT) claims that the characteristics of natural environments can rapidly induce parasympathetic dominance, reduce sympathetic arousal and accelerate the return of physiological indicators such as blood pressure, heart rate, and skin conductance to baseline levels [12]. Concurrently, it effectively lowers the secretion of stress hormones like cortisol and alleviates muscular tension [13]. Meanwhile, the Attention Restoration Theory (ART) declares that the rich yet gentle stimuli within natural settings can elicit involuntary attention, allowing directed attention to rest and thereby restoring cognitive function [14,15].

In previous empirical studies, environmental restoration experiment exposure methods have undergone iterative development from early laboratory-based static images or screen video substitute exposure [12] to field walks or quasi-experiments in natural settings to enhance ecological validity [16], followed by the gradual introduction of explicit manipulation of ‘immersion’ and early virtual nature exposure [17,18]. Over the past decade, alongside advances in digital imaging capture and virtual simulation technologies, research has applied ‘walk-through’ materials recorded from pedestrian height to conduct more detailed comparisons of diverse urban micro-scenes [19]. Additionally, immersive presentation has expanded from single-modal visual experiences to multisensory virtual experiments and higher-fidelity immersion systems, enabling the investigation of more complex scenarios and transitional effects [20,21]. Concurrently, a series of methodological comparative studies (examining differences in effects between photo slideshows and 360° videos within HMDs [22]; comparing presentation variations in the same 360° video on HMDs versus PC screens [23]; and evaluating recovery performance in green/blue/historical environments under immersive versus flat presentations [24]) reveal a trend: while maintaining experimental control, exposure materials are transitioning from static and 2D presentations towards first-person dynamic immersive presentations that are closer to actual walking cues [25,26]. This trend provides a methodological foundation for reconstructing dynamic walking exposure in laboratories, yet gaps remain in the waterfront walkway setting [16,27,28].

Despite considerable progress in restorative environmental research, existing studies still exhibit shortcomings such as insufficient subject coverage and inconsistencies in experimental design and exposure settings when applying relevant methodologies to dynamic walking exposure on urban waterfront walkways. Firstly, current research on restorative views primarily originates from typical green spaces like forests and parks, but quantitative empirical evidence for waterfront settings remains limited [9,29]. Secondly, while recent studies have employed real walking or first-person ‘simulated walking’ to investigate participants’ dynamic experiences during movement [30,31], research within waterfront walkway settings exhibits considerable variation in exposure medium (static, 2D, 360°, immersive VR), viewpoint configuration, exposure duration (duration, speed, pace), and scene segmentation criteria. These differences reduce comparability between studies and hinder the formation of an evidence base [32]. Previous studies have primarily relied on subjective scales or incorporated only a limited number of physiological indicators in variable selection, resulting in insufficient support for explanations at the mechanistic

level [32]. Accordingly, the restorative effects of waterfront paths under dynamic exposure conditions and their psychophysiological mechanisms require further validation.

In recent years, an increasing body of work has used immersive VR and 360° video to examine short-term restoration and stress recovery and to compare different immersion levels and display media [33,34]. However, the current evidence base remains fragmented because exposure dose parameters (e.g., duration and pace) vary substantially across studies, scene segmentation and grouping criteria are inconsistent, and few studies integrate design-relevant visual quantification with multimodal physiological evidence. Reviews and meta-analyses generally support the potential of virtual nature exposure to improve stress- and affect-related outcomes, yet they also report notable heterogeneity in protocols and outcome measures, which limits cross-study comparability and constrains translation into actionable built-environment design parameters [35,36]. Therefore, this study is needed at both the theoretical and practical levels. Theoretically, we test whether, under first-person dynamic walk-through exposure, typology-level differences in pedestrians' visual experience elicit immediate autonomic and affective shifts consistent with restorative environment theories. Practically, we convert panoramic visual composition into interpretable and quantifiable targets to support evidence-informed planning and retrofitting of waterfront walkways. We selected the Kuang River Greenway in Hefei, China, as the case study because it represents a typical linear urban waterfront corridor with high daily use and clear along-route variability in blue–green openness and built or hardscape dominance, enabling comparisons of distinct scene typologies under an identical exposure dose. China-based studies have also begun to examine restorative outcomes in waterfront or VR-simulated environments, underscoring the relevance of this topic and the need for standardized, dose-controlled dynamic exposure protocols [37].

With recent advances in dynamic video and immersive virtual reality (VR) technology, it has become possible to recreate first-person dynamic visual exposure under controlled conditions [34,38]. Dynamic video preserves continuous motion cues and scene transitions, whereas immersive VR enables the standardized delivery of exposure content and duration in laboratory settings, supporting more repeatable protocols [34,39]. In addition, some studies report stronger stress reduction and mood benefits with panoramic head-mounted display (HMD) VR than with flat images [23,39]. Therefore, an increasing number of scholars have recently begun employing immersive methods such as head-mounted VR and VR Caves [21] to simulate natural exposure scenarios. This approach allows for stricter control of environmental variables and enables deeper exploration of the mechanisms governing human–environment interactions [34,36].

To address these research gaps, this study established an integrated experimental framework. Employing image semantic segmentation techniques, we extracted the proportion of various visual elements from panoramic images, thereby transforming the visual composition of waterfront walkways from subjective descriptions into quantifiable variables that can be replicated [40,41]. Five semantic visual indicators were developed: Green View Index (GVI), Water View Index (WVI), Sky View Index (SKVI), Hardscape View Index (HVI), and Built-Structure View Index (BVI). These metrics characterize the visual composition of blue elements, green elements, spatial openness, hard surfaces, and built elements within a scene, along with their interrelationships [42–47]. To circumvent the issues of internal variation masking and inconsistent grouping criteria arising from the 'natural–urban' dichotomy or sparse artificial grouping in prior studies [31], this study normalized the aforementioned indicators and employed K-means unsupervised clustering to derive four typical scene types [48,49]. These were manually interpreted and named based on indicator characteristics and representative panoramic images: Vegetation-Enclosed (VE), Built-Dominant (BD), Hardscape-Plaza (HP), and Blue-Open (BO). To control the

confounding effects of exposure dose variation (particularly where exposure duration and walking speed may concurrently influence psychological experience and physiological arousal), the VR exposure period employed fixed-speed and fixed-duration first-person dynamic VR exposure corresponding to the four scene types. At identical walking speeds and exposure durations, differences among participants across various scene types in the experiment primarily reflect variations in the spatial composition and landscape rhythm, rather than differences in the exposure dosage [50]. This study employs a multimodal assessment approach combining subjective questionnaires with objective physiological synchronous recordings. For subjective questionnaires, the International Positive and Negative Affect Schedule Short Form (I-PANAS-SF) and Semantic Differential (SD) scales are utilized to capture real-time emotional fluctuations and variations in scene perception [51,52]. In parallel, electrocardiogram (ECG), electrodermal activity (EDA), electromyography (EMG), and respiration (RESP) were simultaneously recorded to reflect autonomic nervous system activity changes and objectively characterize stress load and relaxation levels [53–56]. Together, this framework integrates semantic visual quantification, scene typology, controlled dynamic exposure, and psychophysiological responses, providing a controllable and reusable methodological basis for testing the restorative differences and underlying mechanisms in urban waterfront walkways during dynamic walking.

To further anchor this methodological framework in established perceptual and cognitive theories, we draw on classical concepts of environmental legibility, visual complexity, and spatial sequence. Environmental legibility refers to how easily people can recognize and organize urban elements into a coherent mental representation, which can reduce uncertainty and cognitive load during navigation and thereby influence affective and stress-related responses [57]. Cullen's townscape theory and 'serial vision' further emphasize that pedestrians experience cities as a sequence of unfolding views; changes in enclosure, openness, and salient elements structure moment-to-moment appraisal during movement [58]. Recent studies have also operationalized Lynch-like perceptual constructs using street-level imagery and AI, indicating that measurable visual cues can be linked to human perception and behavior at scale [59]. In line with these perspectives, our view-based indices provide an operational bridge: higher GVI/WVI and SKVI reflect salient blue–green cues and openness that support scene organization, whereas higher HVI/BVI indicate stronger hard-edge and built dominance that may increase visual load. Accordingly, the four derived typologies can be interpreted as contrasting combinations of legibility and visual load along a dynamic pedestrian viewpoint, enabling theory-informed interpretation of the observed psychophysiological differences.

We implemented a fixed-speed, fixed-duration first-person dynamic exposure design to examine how visual composition relates to restorative responses in an urban waterfront walkway context.

The research objectives are as follows:

- (1) With walking speed and exposure duration held constant, compare the differences in psychological and physiological recovery effects between four types of waterfront walkways composed of distinct visual elements;
- (2) Under fixed exposure dose conditions, characterize the impact of key visual characteristics—such as visual rhythm, spatial openness, and built element load—on immediate recovery effects;
- (3) Evaluate whether typology-level differences in semantic visual indices align with typology-level differences in psychophysiological responses, providing an interpretable basis for explaining recovery variation across scene types.

The research hypotheses are as follows:

H1: *Relative to the resting baseline period, VR exposure will elicit measurable short-term changes in psychological and physiological recovery; mood improvement is expected across typologies, whereas autonomic responses (SCL, RMSSD) may vary by typology.*

H2: *Typologies with higher blue–green visibility (higher WVI or GVI) exhibit autonomic patterns that are more relaxed (lower SCL and higher RMSSD) compared to typologies dominated by buildings or hardscapes.*

H3: *Between-typology differences in semantic indices (GVI/WVI/SKVI/HVI/BVI) will show a consistent ordering with SD ratings and with the direction of physiological responses.*

2. Materials and Methods

2.1. Overview

This study employed a within-subject repeated measures design to investigate the effects of different waterfront walkway scenarios on participants' psychophysiological responses during first-person dynamic walking visual exposure [60]. Four types of waterfront walkway scenarios were obtained through video frame extraction, semantic segmentation, and K-means clustering. Their presentation order in the experiment was counterbalanced using a Latin square design. Each scene type constituted an exposure block, with a fixed protocol comprising a 3 min eyes-closed resting baseline period, 50 s of immersive exposure, removal of the HMD followed by completion of subjective questionnaires, and a 5 min inter-block rest period (as illustrated in Figure 1). Following prior 360° video-based virtual exposure research that adopted 50 s scene segments under a dose-controlled viewing protocol, we set the exposure duration to 50 s per clip to ensure a fixed and comparable stimulus dose across typologies [61]. In addition, before the formal experiment, we conducted a pilot feasibility run with 10 participants to evaluate participant burden and VR comfort. The pilot indicated that viewing all clips in a single prolonged session and completing consolidated post-exposure questionnaires at the end increased fatigue, cybersickness, and boredom. It also reduced rating accuracy because participants' recall of earlier clips became less distinct. Therefore, we revised the procedure to the current structure with immediate post-clip questionnaires and controlled overall session length, while retaining the fixed 50 s exposure duration per clip for dose standardization. Accordingly, this study interprets physiological outcomes as immediate autonomic responses during the immersive exposure window, rather than complete recovery trajectories that typically require longer observation periods. The study compared (i) physiological indicators and subjective mood ratings between the resting baseline period and VR exposure period within each scenario, and (ii) responses during the VR exposure period across the four scenario types.

The human figure, wearable-device graphics, and icon elements in Figure 1 (Phase 2) were generated using Google Gemini (Gemini 3 Pro Image, accessed 10 December 2025) and were subsequently manually redrawn and edited, and then assembled using Adobe Illustrator (version 24.3) and Adobe Photoshop (version 21.2.12) to create the final schematic. The authors reviewed and curated the generated visual elements. No generative artificial intelligence (GenAI) tools were used to generate, modify, or analyze the study data or results.

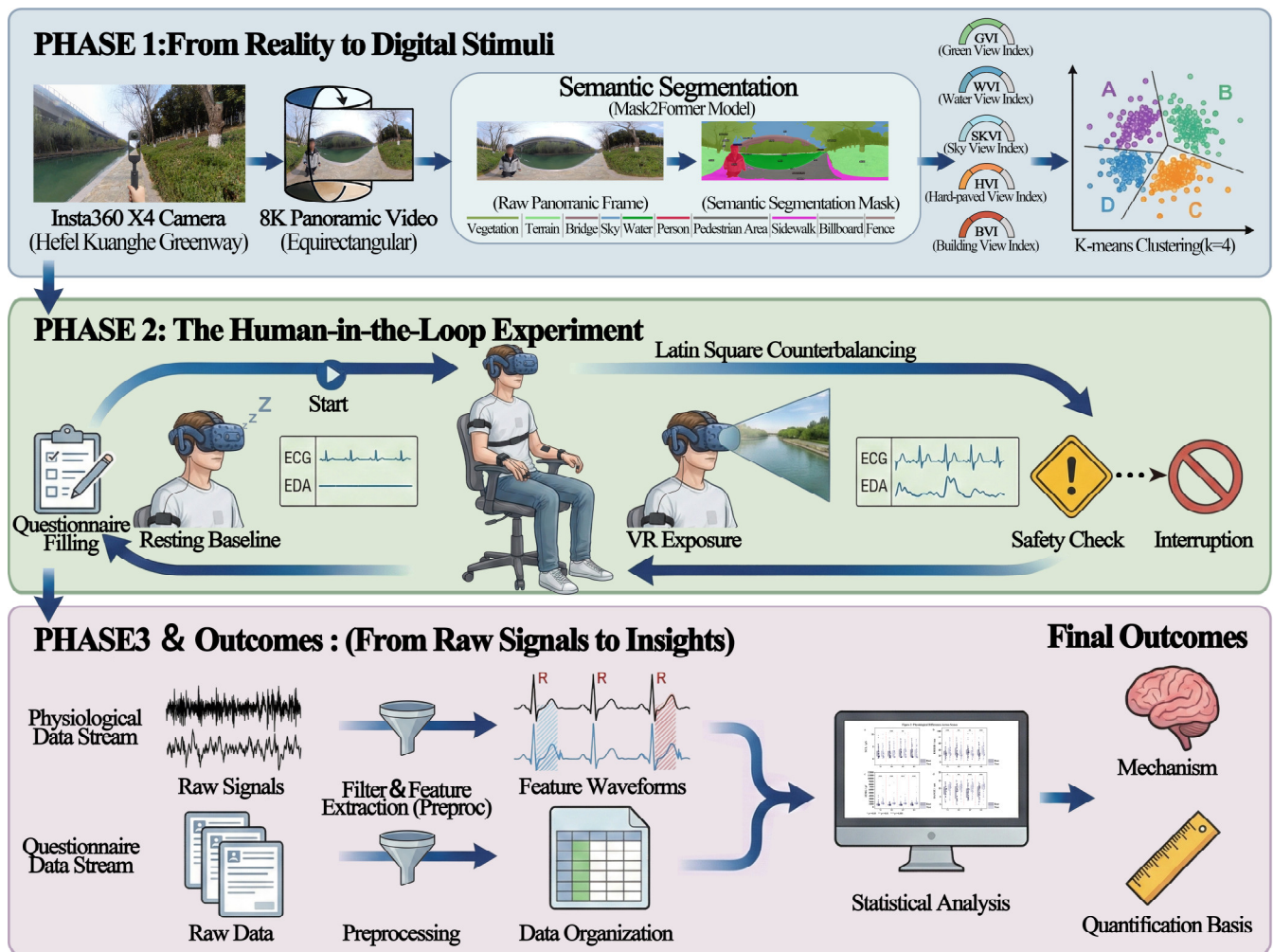


Figure 1. The overall research framework. The workflow consists of three phases: (1) Phase 1: From Reality to Digital Stimuli, involving panoramic data acquisition using an Insta360 X4 camera, semantic segmentation via the Mask2Former model to calculate visual indices (GVI, WVI, SKVI, HVI, and BVI), and K-means clustering to categorize scene types. (2) Phase 2: The Human-in-the-Loop Experiment, illustrating the specific experimental procedure arranged by Latin square counterbalancing. This phase comprises the cyclic process of questionnaire filling, resting baseline recording, dynamic VR exposure, and safety checks, with synchronous physiological monitoring (ECG, EDA). (3) Phase 3 and Outcomes (From Raw Signals to Insights), describing the data processing pipeline from raw signals to feature extraction and statistical analysis to derive statistical evidence and quantification basis.

2.2. On-Site and Virtual Reality Simulations

This study selected a real-world waterfront walkway as the site for panoramic VR (360°) video capture, namely the Kuang River Greenway in Hefei, China (Hefei's Municipal Government and Cultural New District). Choosing a China-based case study strengthens the practical relevance of the findings for rapidly urbanizing built-environment contexts where waterfront corridor planning and retrofitting are ongoing priorities, and it provides an empirical basis for design-oriented interpretation under controlled first-person dynamic exposure. The use of an authentic site rather than virtual modeling aimed to enhance the realism and immersion of the VR video, thereby ensuring the validity of the scene exposure's psychophysiological effects. Spanning 11.2 km, the Kuang River Greenway connects multiple nodes including Swan Lake and the Olympic Sports Center, exhibiting typical linear waterfront corridor characteristics. Importantly, the corridor shows clear within-route variability in blue–green openness and built or hardscape dominance, which supports

identifying distinct scene typologies while holding exposure dose constant. It therefore provides stable, controllable, and repeatable conditions for dynamic visual exposure during walking (as illustrated in Figure 2).

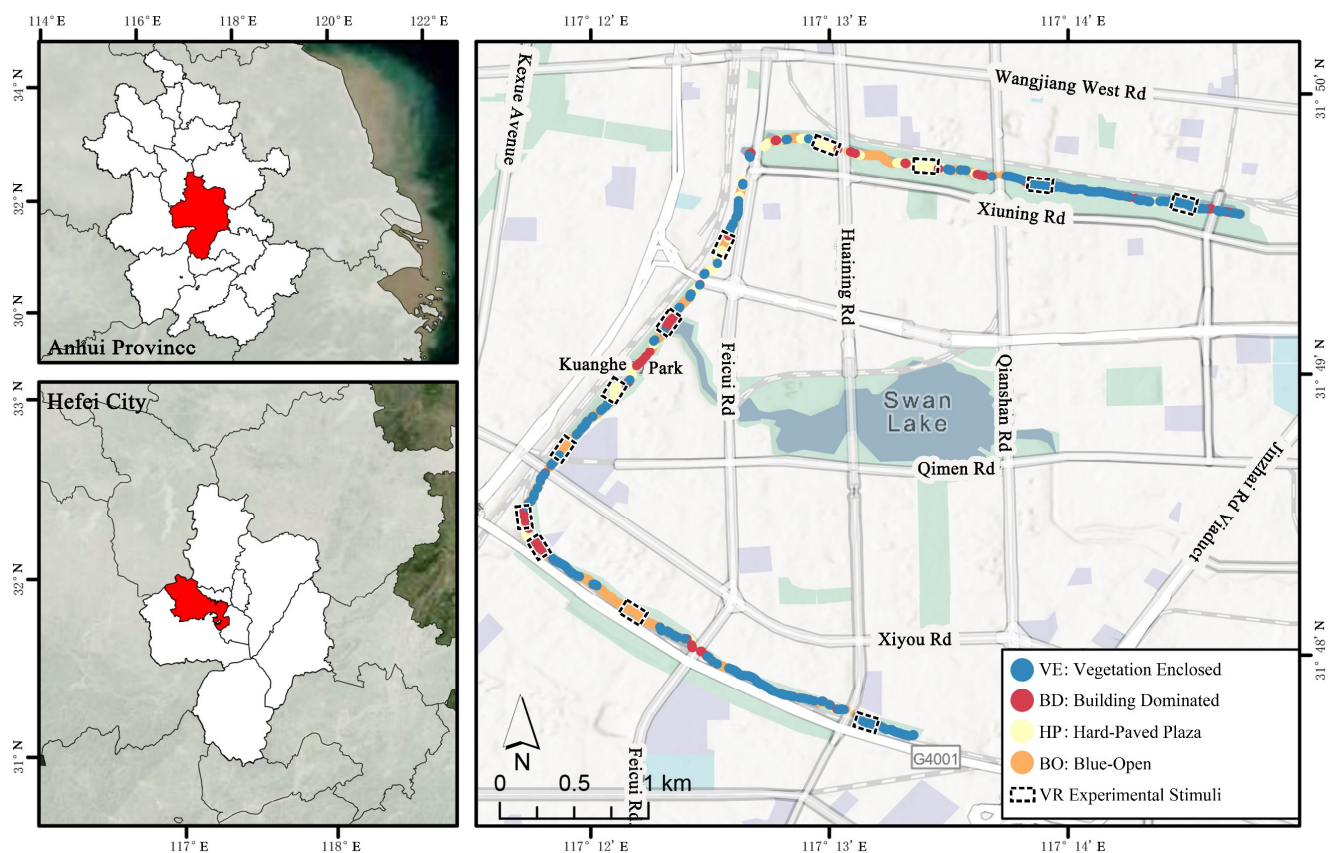


Figure 2. Location of the study area and spatial distribution of the experimental route. The left insets indicate the geographic position of Hefei City in Anhui Province, China, and Shushan District within Hefei City. In the insets, the study location is highlighted in red. The main map displays the experimental route along the Kuang River Greenway, classified into four scene types: Vegetation-Enclosed (VE), Built-Dominant (BD), Hardscape-Plaza (HP), and Blue-Open (BO). The black dashed boxes indicate the specific sampling locations of the 12 VR experimental video segments (50 s each).

Panoramic video was recorded from 14:00 to 16:00 on 8 March 2025, under clear weather with temperatures around 20 °C. The camera operator walked along the riverside path of the Kuang River Greenway and captured footage using a panoramic camera (Insta360 X4; Insta360, Shenzhen, China) mounted on a handheld selfie stick. The camera was operated at a height of approximately 1.7 m and recorded in parallel 7680 × 3840 pixels and 24 fps. The camera operator simultaneously wore a multimodal wristband (PTCK-M; Beijing psychtech technology, Beijing, China) to record GPS positioning of the filming trajectory and environmental data (temperature, humidity, atmospheric pressure) for frame localization and experimental environment documentation.

The original footage was processed using Insta360 Studio software (version 5.6.1) to apply FlowState stabilization, orientation locking, stitching, color enhancement, ambient noise removal, and other adjustments. This resulted in an exported 8K panoramic video (7680 × 3840, 200 Mbps).

Then, frames were extracted with FFmpeg (version 7.1.1) at 1 fps (6124 frames total), with each frame geotagged to GPS coordinates within ArcGIS Pro (version 3.1.5). To reduce area distortion inherent in the equirectangular representation of panoramic imagery, frames were reprojected to an equal-area cylindrical projection prior to semantic segmentation, so that pixel area better corresponds to ground area. Subsequently, construction zones, urban road intersections, tunnels, and other interfering scenes were removed from the video. This yielded 5647 valid frames for analysis.

This study employed an off-the-shelf Mask2Former model [62] to perform semantic segmentation on panoramic images. The model generated pixel-level semantic masks for each frame using the 66-category label system of Mapillary Vistas [63]. From these outputs, we retained sixteen categories that were present in the waterfront walkway scenes and relevant to visual-index construction, while other categories were excluded from subsequent analyses. For each retained category, we calculated its area proportion as the number of pixels assigned to that category divided by the total number of pixels in the frame.

Because pixel-level ground-truth annotations are not available for the panoramic frames in the study area, this study cannot compute a dataset-specific mean IoU for our study area frames. For reference, Mask2Former reports 63.2 mIoU under single-scale inference and 64.7 mIoU under multi-scale inference on the Mapillary Vistas validation set [62]. To reduce the potential influence of automatic segmentation errors caused by specular water reflections and complex backgrounds on index computation, this study conducted manual spot-checking as a post-segmentation quality control step. Specifically, a stratified random sample of 5% of the final analytic images was inspected, totaling 282 frames out of 5647, with targeted attention to frames with large visible water surfaces and frames with complex water–sky boundaries. The spot-checking suggested that the model outputs were generally stable, and no systematic or large-scale obvious mis-segmentation was observed in the sampled frames. However, local boundary uncertainty may still occur in regions with water reflections or mixed boundaries. To mitigate its influence on index estimation, frames with obvious errors or severe blur were excluded where identified prior to index calculation, and indices were summarized at the clip level to reduce the impact of occasional frame-level segmentation errors. This clip-level aggregation helps smooth sporadic mis-segmentation in individual frames by averaging indices over the continuous exposure window, thereby improving the robustness of typology-level comparisons.

Based on the 16 category proportions, we constructed five semantic visual indices: GVI [42], SKVI [45], WVI [43], HVI [46], and BVI [46] (as illustrated in Figure 3). The first three represent natural ecological elements within the waterfront environment, while the latter two denote built-environment elements. Following normalization of the indicator matrix across 5647 images, K-means clustering (with silhouette coefficient determining optimal cluster number $k = 4$) yielded four typical scene categories. These were interpreted and named based on indicator characteristics and representative panoramic images: waterfront walkway scenes were classified into VE, BD, HP, BO [48] (cluster centers shown in Table 1). The typology prevalence in the full frame set is reported in Table 1 (VE: 28.5%, BD: 8.8%, HP: 18.5%, BO: 44.2%). Based on video segments continuously belonging to the same category, three consecutive 50 s video clips were selected from each category (totaling twelve clips).

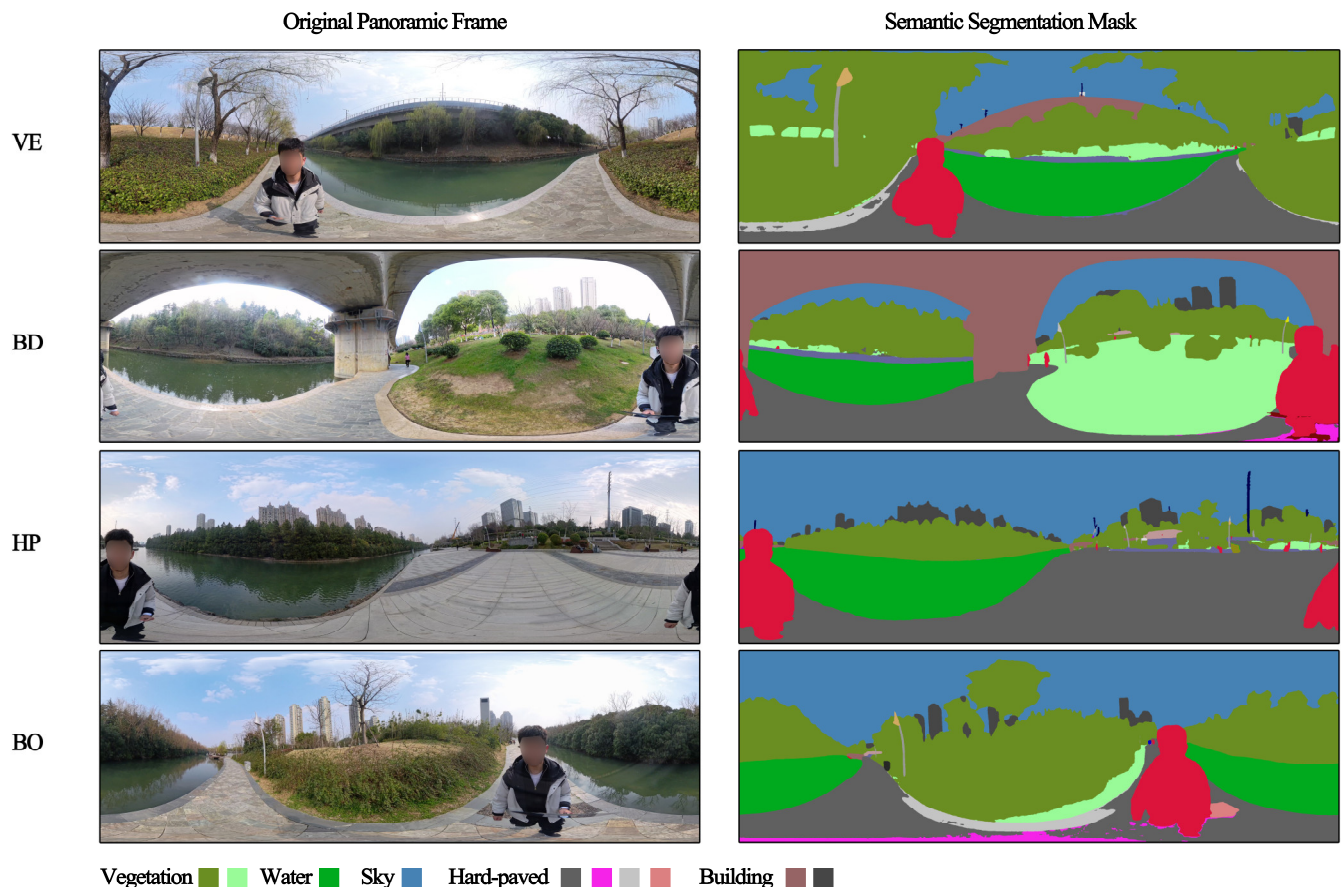


Figure 3. Representative examples of semantic segmentation results across four scene typologies. The figure displays paired images for each of the four identified scene clusters: VE (Vegetation-Enclosed), BD (Built-Dominant), HP (Hardscape-Plaza), and BO (Blue-Open). The **left** column shows the cylindrical equal-area reprojected panoramic frames captured at the Hefei Kuang River Greenway. The **right** column presents the corresponding semantic segmentation masks generated by the Mask2Former model. These masks classify visual elements into specific categories (as shown in the bottom legend) to calculate the visual indices: vegetation (green tones) for GVI, water (cyan) for WVI, sky (blue) for SKVI, hard-paved (gray / pink tones) for HVI, and building (brown/gray tones) for BVI. The red area represents the photographer, which was excluded from the index calculation. Other minor classes appearing in the masks (e.g., streetlights and utility poles) are not included in the five index calculations and are retained only for visual completeness.

Table 1. Cluster centers and prevalence of the four waterfront scene typologies based on five semantic visual indices (BVI, GVI, WVI, HVI, and SKVI).

Scene Type	BVI	GVI	WVI	HVI	SKVI	<i>n</i> (Frames)	%
VE	0.029	0.524	0.086	0.175	0.117	1610	28.5
BD	0.311	0.235	0.078	0.065	0.212	495	8.8
HP	0.039	0.192	0.101	0.267	0.310	1044	18.5
BO	0.032	0.402	0.099	0.177	0.213	2498	44.2

Note: Values represent the normalized mean proportion of each semantic component within the field of view for each cluster. *n* (frames) and % indicate the number and percentage of frames assigned to each typology (total = 5647 frames). VE = Vegetation-Enclosed; BD = Built-Dominant; HP = Hardscape-Plaza; BO = Blue-Open. BVI = Built-Structure View Index; GVI = Green View Index; WVI = Water View Index; HVI = Hardscape View Index; SKVI = Sky View Index.

2.3. Participants

This study recruited 50 healthy adults (25 females) through online and offline channels, comprising 49 students from the local college and one on-campus research staff member,

aged 18–30 years (see Table 2). All participants had no history of cardiovascular, neurological, or psychiatric disorders, were not taking medications affecting physiological or psychological states, and abstained from caffeine and alcohol for 24 h. Participants voluntarily enrolled, signed informed consent forms, and received small gifts and monetary compensation upon completion.

Table 2. Demographic characteristics of participants and their visitation frequency to the Kuang River ($N = 50$).

Characteristics	Category	<i>n</i> (%)
Gender	Male	25 (50.0)
	Female	25 (50.0)
Age	18–25	47 (94.0)
	26–30	3 (6.0)
Education	Undergraduate	14 (28.0)
	Postgraduate	36 (72.0)
Occupation	Students	49 (98.0)
	Research Staff	1 (2.0)
Academic major	Architecture and design-related	32 (64.0)
	Other disciplines	18 (36.0)
Kuang River visit frequency (past year) ¹	Never	40 (80.0)
	Once	7 (14.0)
	2–3 times	3 (6.0)

Note: Data are presented as number (percentage). ¹ The specific question asked was: ‘Have you visited the Kuang River in Hefei’s Municipal Government and Cultural New District in the past year?’.

Regarding sample size, this study employed G*Power (v3.1) for a priori power analysis. Referencing reported effect sizes from comparable immersive virtual nature exposure studies, and to avoid overestimation due to inter-study variability, a more conservative small-to-medium effect size of $f = 0.2$ was adopted. The significance level was set at $\alpha = 0.05$, with test power defined as $1 - \beta = 0.80$. The power analysis indicated a minimum required sample size of $N = 44$. Considering potential physiological signal artifacts and possible dropouts, the study ultimately enrolled 50 participants to ensure statistical robustness.

This study adhered to the principles of the Declaration of Helsinki and was approved by the Science and Technology Ethics Committee of Anhui Jianzhu University (approval no. 2025008; approved on 15 June 2025). All participants provided written informed consent prior to the experiment. Participants were free to withdraw at any time without penalty, and withdrawal did not affect any compensation already received. Research data were anonymized prior to statistical analysis and were used solely for scientific research purposes.

2.4. VR Environments and Equipment

The experimental exposure comprised twelve 50 s segments of 360° panoramic video (7680 × 3840 resolution), presented via a VR head-mounted display (HMD; Vive Pro Eye, HTC Corporation, Taoyuan City, China). The video was decoded, distortion-corrected, and rendered in real time by a workstation host, then delivered to the headset via SteamVR (version 2.10.4) (host configuration: Intel Core i7-13700KF, NVIDIA RTX 4090, 32 GB RAM). Experimental workflow control and synchronized physiological signal acquisition were achieved using ErgoLAB software (version 3.0 on the same host computer, ensuring temporal consistency between exposure presentation and multimodal data recording. Physiological signals were acquired via the ErgoLAB wireless human factors physiological recorder (version 4.0, Beijing Kingfar Technology Co., Ltd., Beijing, China), including electrocardio-

gram (ECG), pulse wave (PPG), electrodermal activity (EDA), surface electromyography (EMG), chest strap respiration (RESP), and skin temperature (SKT).

2.5. Experimental Design and Procedure

The experiment was conducted in a laboratory maintained at 24 °C and 50% relative humidity, with low ambient noise (~20 dB). We used a within-subject counterbalanced four-block design, with each block corresponding to a distinct scenario category. Upon arrival, the experimenter explained the procedure and answered their questions. Participants then completed a pre-experiment subjective questionnaire on their mobile phones, which included basic personal information and the I-PANAS-SF mood scale [51]. The experimenter fitted the ErgoLAB wireless human factors physiological recording system (recorder and sensors) and the HMD. All channels were calibrated and recording timestamps were synchronized. Participants then remained seated in the virtual environment for 1 min to acclimate to and view instructions.

The formal experiment comprised four consecutive blocks, with their sequence counterbalanced using a Latin square design. In each block, one of three pre-prepared clips was selected for the corresponding category. Each participant viewed one clip per category without repetition. Across participants, clip assignment was approximately balanced so that each clip appeared with a similar frequency. The procedure for each block was as follows: After donning the headset, participants sat with eyes closed for 3 min to collect resting baseline physiological data; upon receiving an in-headset prompt and verbal instruction, participants opened their eyes; they then viewed a 50 s panoramic video (during VR exposure, participants sat in a swivel chair and could freely adjust their viewing angle, though large body movements were discouraged); participants then removed the headset after the video and completed the block's subjective questionnaire (approximately 3 min, including the Landscape SD Method Evaluation Scale and the I-PANAS-SF emotion scale); there was an inter-group rest period of 5 min.

Following each VR exposure period, experimenters asked participants about dizziness or nausea and recorded any pauses. When participants experience discomfort during the viewing process, follow this tiered protocol: Severe discomfort requires immediate termination of the experiment, providing appropriate reassurance to the subject, and excluding the data from that session. Moderate discomfort warrants a temporary suspension of the experiment until the subject recovers. Mild discomfort necessitates extending the rest period between blocks. The experiment lasts 45 min in total, with the cumulative VR exposure time kept below 4 min to mitigate potential fatigue and discomfort factors [64]. Upon completion, the experimenter assisted with device removal and provided participants with appropriate compensation (as illustrated in Figure 4).

2.6. Indicators and Scales

2.6.1. Physiological Indicators

Electrodermal activity (EDA) is expressed as skin conductance level (SCL) to indicate an individual's arousal state. This study employs skin conductance level to characterize sustained arousal, calculating the relative change rate (ΔSCL) during the VR exposure period relative to the resting baseline period as the primary outcome measure:

$$\Delta SCL = \frac{SCL_{stim} - SCL_{base}}{SCL_{base}} \quad (1)$$

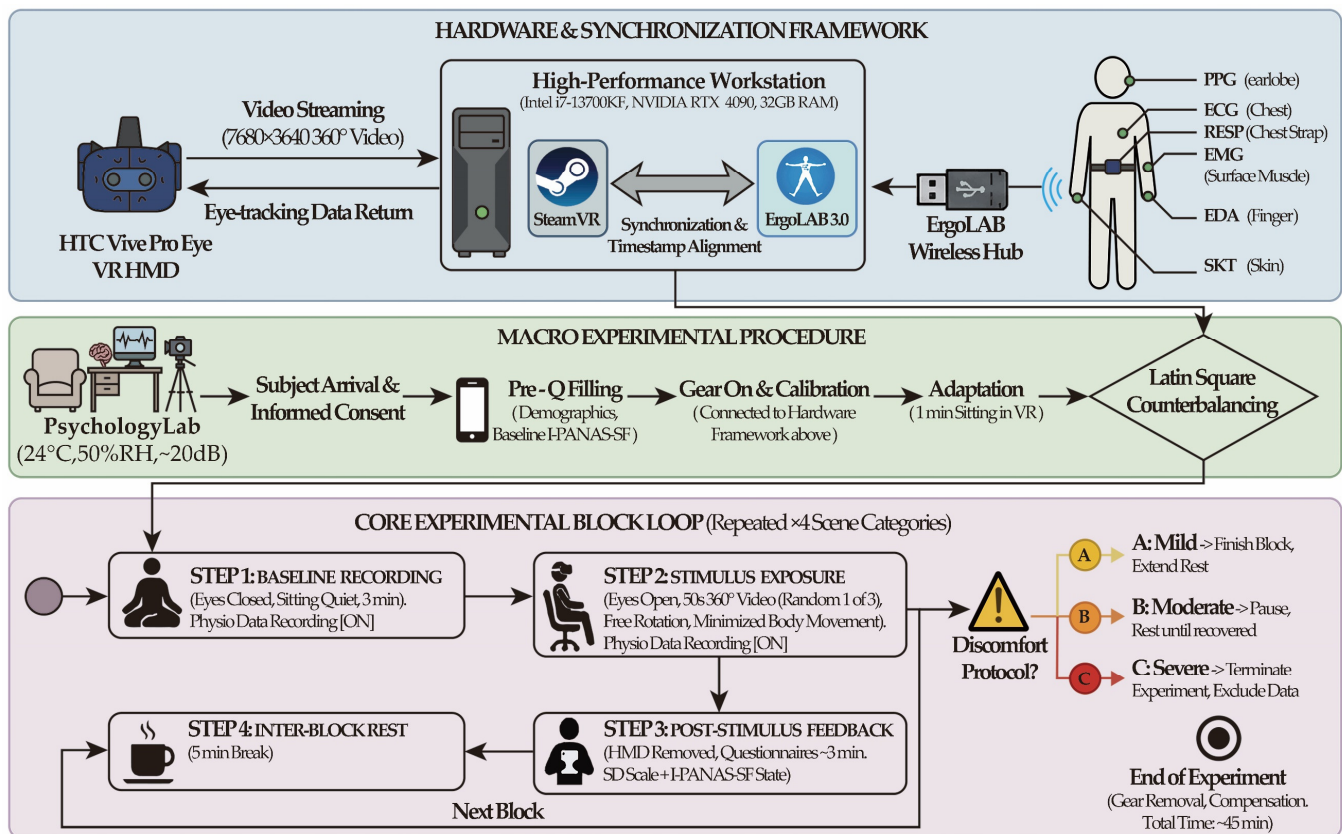


Figure 4. Three-layer schematic of hardware synchronization and the experimental workflow. **Top:** Workstation-based timestamp alignment between the HTC Vive Pro Eye (video streaming/eye-tracking return) and ErgoLAB 3.0. **Middle:** Consent, pre-questionnaire, device fitting, VR adaptation, and Latin square counterbalancing. **Bottom:** Repeated block with a 3 min baseline, 50 s exposure, post-stimulus questionnaires, and a 5 min break, monitored with a graded discomfort protocol.

The mean SCL during the VR exposure period is denoted as SCL_{stim} , while the mean SCL during the resting baseline period is denoted as SCL_{base} . A value of $\Delta SCL > 0$ indicates that arousal levels during the VR exposure period exceed those during the resting baseline period.

Heart rate variability (HRV) is calculated from electrocardiogram signals by extracting RR intervals. Short-term HRV is measured using the root mean square of successive differences (RMSSD) between adjacent RR intervals, with higher RMSSD indicating stronger parasympathetic activity and a more relaxed state. Surface electromyography (EMG) is recorded via electrodes placed on the extensor muscles of the subject's right forearm. Higher iEMG values indicate stronger muscle activation and greater somatic tension. The integral of the entire EMG signal (iEMG) during the VR exposure period is calculated to quantify muscle activity intensity. As forearm EMG is insensitive to affective valence, this metric primarily monitors non-specific tension activity to supplement interpretations of EDA and HRV variations. Respiratory rate was recorded via chest strap sensors. This study calculated the range of respiratory rate (RRR) for each experimental phase, defined as the difference between the maximum and minimum respiratory rates during that period (unit: rpm). This metric quantifies respiratory rhythm instability. Higher range values indicate pronounced fluctuations in breathing rhythm, typically associated with alternating rapid breathing and pauses during emotional arousal, tension, or stress states.

2.6.2. Subjective Scale

Pre- and post-experimental questionnaires were employed to gather subjective emotional responses and landscape environmental evaluations. For emotional assessment, the Chinese version of the I-PANAS-SF Emotional Scale was used. This scale comprises ten emotional adjectives (five positive and five negative), rated on a five-point Likert scale (1 = not at all, 5 = extremely), with higher scores indicating greater intensity of the corresponding emotion (details in Table 3). Participants' overall emotional state during the week preceding the experiment served as the baseline. Immediate emotional responses were reported immediately after each video viewing, yielding positive affect (PA) and negative affect (NA) scores for each scene. Regarding landscape environment, this study designed a Semantic Differential (SD) questionnaire (details in Table 4) based on the relevant waterfront landscape evaluation literature and the site's actual characteristics. It comprises fifteen pairs of bipolar adjectives covering landscape elements (e.g., accessibility, visual aesthetics, spatial variation), ecological elements (e.g., vegetation coverage, environmental cleanliness), and socio-cultural elements (e.g., public engagement, safety, recreational diversity). Participants evaluated the scene immediately after viewing each video segment. We will examine the internal consistency reliability and construct validity of each scale in the statistical analysis.

Table 3. Measurement items of the I-PANAS-SF employed in the study.

Positive Affect (PA)	Negative Affect (NA)
Active	Upset
Attentive	Hostile
Determined	Ashamed
Alert ¹	Nervous
Inspired	Afraid

Note: Items were rated on a 5-point Likert scale ranging from 1 (very slightly or not at all) to 5 (extremely). ¹ The item 'Alert' was excluded from the final analysis due to low internal consistency and semantic ambiguity in the study context.

Table 4. The evaluation index system of the Semantic Differential (SD) scale for waterfront landscape perception.

Dimensions	Code	Indicators
Landscape Elements	A1	Accessibility
	A2	Visual Openness
	A3	Hydrophilicity
	A4	Aesthetic Quality
	A5	Landscape Harmony
	A6	Visual Interest
	A7	Spatial Variation
	A8	Rhythm
Ecological Elements	B1	Vegetation Coverage
	B2	Plant Diversity
	B3	Environmental Cleanliness
	B4	Ecological Quality
Socio-cultural Elements	C1	Public Engagement
	C2	Safety of Facilities
	C3	Recreational Diversity

Note: The evaluation employed a 5-point Semantic Differential (SD) scale. Participants rated each indicator based on bipolar adjective pairs ranging from 1 (negative/low) to 5 (positive/high).

2.7. Data Processing

2.7.1. Physiological Data

Physiological signals underwent preprocessing via ErgoLAB software including filtering for noise reduction, R-peak detection, and artifact correction. For each block, the resting baseline phase was defined as the final 30 s of the 3 min resting baseline period constituted, while the VR exposure phase was defined as the subsequent 50 s video viewing segment. We calculated the mean SCL values for the resting baseline and VR exposure periods within each block to compute Δ SCL. Meanwhile, we extracted metrics including RMSSD, total iEMG and range of respiratory rate (RRR) during the resting baseline phase and VR exposure for each period. The organized physiological metric data were used for subsequent statistical analysis comparing intra-group and inter-group differences.

This study employed a within-subject repeated measures experimental design. All 50 participants experienced all four types of waterfront walkway scenes (presentation order randomized and balanced), ensuring comparability of samples across scene conditions. For each physiological indicator, two comparisons were established: ① intra-scene comparison (resting baseline period vs. VR exposure period within the same scene); ② cross-scenario comparisons (between the VR exposure periods of the four scenarios). As the Shapiro–Wilk test indicated significant deviations from normal residual distribution for all metrics ($p < 0.05$), non-parametric statistical methods were employed. Overall inter-scenario differences were assessed using Friedman’s test ($k = 4$), reporting Kendall’s W as the effect size. For clarity, χ^2 (df) denotes the chi-square statistic with degrees of freedom, and Kendall’s W denotes effect size for Friedman’s test. Where significant, pairwise comparisons were further conducted using the Wilcoxon signed-rank test (two-tailed), with Holm–Bonferroni correction applied to control the family-wise error rate (FWER = 0.05; $m = 6$, as four conditions yield $C_4^2 = 6$ pairwise comparisons). Intra-scenario comparisons also employed the Wilcoxon test, with Holm correction applied to paired comparisons between resting baseline and VR exposure periods across all four scenarios ($m = 4$, one paired comparison per scenario). The Wilcoxon effect size was expressed as the correlation coefficient r , calculated as $r = |Z| / \sqrt{N}$, where Z is the standardized statistic and N is the effective paired sample size for that comparison.

2.7.2. Questionnaire Data

The subjective questionnaire data were exported and collated via the Wenjuan Xing (wjx.cn), a Chinese web-based questionnaire platform (accessed on 1 August 2025). Each participant’s baseline PA/NA scores, I-PANAS-SF instantaneous PA/NA scores across four blocks, and SD landscape evaluation scores were consolidated into an Excel spreadsheet and imported into SPSS 27.0 for statistical analysis.

3. Results

3.1. Objective Validation of Scene Visual Features

This study employed the nonparametric Kruskal–Wallis H test to evaluate variations in the semantic visual metrics across different scenarios.

Statistical analysis revealed significant differences between the four scenarios in terms of the GVI ($H(3) = 9.974$, $p = 0.019$) and SKVI ($H(3) = 8.436$, $p = 0.038$). The VE scenario exhibited significantly higher GVI than the HP scenario. By contrast, SKVI was highest in the HP scenario and higher than in the VE scenario (Figure 5).

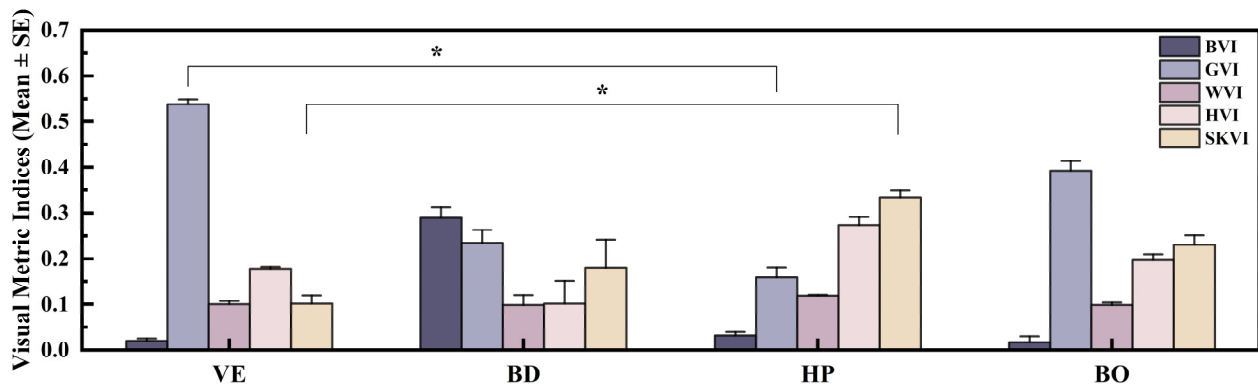


Figure 5. Comparison of visual metric indices across four scene typologies. The bar chart displays the mean values of Built-Structure View Index (BVI), Green View Index (GVI), Water View Index (WVI), Hardscape View Index (HVI), and Sky View Index (SKVI) for each scene category (VE: Vegetation-Enclosed, BD: Built-Dominant, HP: Hardscape-Plaza, BO: Blue-Open). Error bars represent the standard error of the mean (SE). Significant pairwise between-scene differences are indicated by brackets with asterisks, based on the Dunn post hoc test with Bonferroni correction following a Kruskal–Wallis H test. In the figure, asterisks indicate statistical significance (* adjusted $p < 0.05$). Significant differences were observed only for GVI and SKVI, and significance markers are shown accordingly.

Although BVI, HVI and WVI showed no overall differences (all $p > 0.05$), the distribution trends of their mean values (Figure 5) indicate that the building visibility in the BD scenario and the hard surface visibility in the HP scenario still stayed the numerically highest respectively, consistent with the predefined scene classification characteristics. WVI varied little, consistent with all scenes being sampled along the same waterfront walkway.

3.2. Physiological Response

3.2.1. In-Scene Immediate Response: Resting Baseline Period vs. VR Exposure Period

Compared to the resting baseline period, physiological changes across different scenarios exhibited marked differentiation. For interpretation, higher SCL and iEMG indicate higher arousal or tension, higher RMSSD indicates stronger parasympathetic regulation, and higher RRR indicates greater breathing-rate variability. Skin conductance level (SCL) significantly increased from the resting baseline to the VR exposure period in Scenario BD ($Z = 3.72$, $p < 0.001$, $r = 0.53$) and Scenario HP ($Z = 3.19$, $p < 0.001$, $r = 0.45$), while no significant changes in SCL were observed in Scenarios VE and BO ($p_{Holm} \geq 0.113$). Heart rate variability (RMSSD) exhibited an inverse pattern: RMSSD significantly increased relative to resting baseline in Scenario VE ($Z = 3.87$, $p < 0.001$, $r = 0.55$) and Scenario BO ($Z = 3.93$, $p < 0.001$, $r = 0.56$), which showed significantly elevated RMSSD relative to resting baseline, indicating enhanced parasympathetic activity, whereas RMSSD decreased significantly in Scenario BD ($Z = 2.98$, $p = 0.006$, $r = 0.42$) and Scenario HP ($Z = 2.71$, $p = 0.007$, $r = 0.38$). Forearm electromyography (iEMG) was markedly elevated across all scenarios compared to resting baseline ($p_{Holm} < 0.001$ for all), while respiratory rate range (RRR) significantly increased in all scenarios ($p < 0.05$), with the greatest increase observed in Scenario BO (details in Figure 6). All pairwise comparison p -values underwent Holm–Bonferroni correction (p_{Holm}).

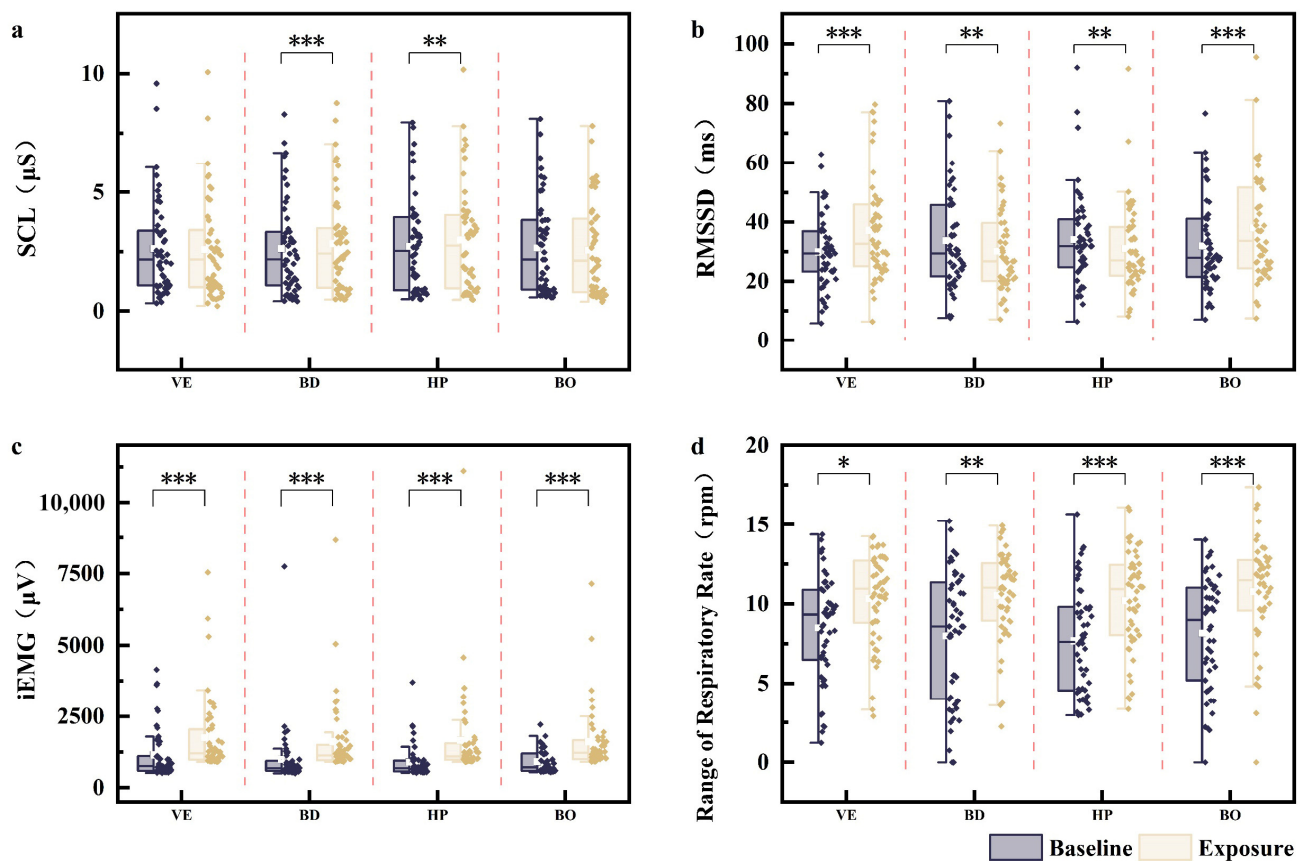


Figure 6. Within-subject comparison of physiological responses between the resting baseline and dynamic VR exposure phases across the four scene typologies. (a) Skin conductance level (SCL), indicating physiological arousal. (b) Root mean square of successive differences (RMSSD), reflecting parasympathetic regulation. (c) Integrated electromyography (iEMG), reflecting skeletal muscle activation and somatic tension. (d) Range of respiratory rate (RRR), reflecting breathing variability. Typologies: Vegetation-Enclosed (VE), Built-Dominant (BD), Hardscape-Plaza (HP), and Blue-Open (BO). Boxplots show the median and interquartile range with individual observations overlaid; baseline is shown in dark purple and exposure in light beige. The red dashed lines are visual separators used only to improve readability between scene typologies and have no additional meaning. Differences between phases were determined by Wilcoxon signed-rank tests with Holm–Bonferroni correction. In the figure, asterisks indicate statistical significance (* adjusted $p < 0.05$, ** adjusted $p < 0.01$, *** adjusted $p < 0.001$).

3.2.2. Differences in Scenario Types: A Comparison of VR Exposure Period Responses

The type of scene significantly influenced the overall level of physiological indicators. ΔSCL is reported as the percentage change from baseline; positive values indicate higher arousal during exposure than baseline, whereas negative values indicate reduced arousal. Using the skin conductance change rate ΔSCL as the dependent variable, the Friedman test revealed significant differences among the four scene conditions ($\chi^2(3) = 35.23$, $p < 0.001$, Kendall's $W = 0.235$). Post hoc Wilcoxon comparisons revealed that ΔSCL was significantly lower in VE and BO compared to BD and HP (all adjusted $p < 0.001$), while no significant differences existed between VE and BO or BD and HP. The median ΔSCL during VR exposure periods across scenes was approximately VE -2% , BO -3% (slightly below resting baseline) vs. BD $+6.7\%$, HP $+4.4\%$ (above resting baseline). Thus, scenes VE and BO with richer natural elements did not induce increased skin conductance (reduced arousal levels), whereas the more artificial scenes BD and HP elicited sustained higher arousal levels. RMSSD also showed significant differences between scenes ($\chi^2(3) = 48.41$, $p < 0.001$, $W = 0.323$). Overall, natural scenes VE and BO corresponded to higher RMSSD

values than built scenes BD and HP. Post hoc comparisons revealed that RMSSD for VE and BO was significantly higher than that for BD and HP ($p < 0.001$ for all comparisons), with no significant differences between VE and BO or BD and HP. The median RMSSD in the VE and BO scenarios was approximately 33 ms, markedly higher than the 27 ms observed in the BD and HP scenarios, indicating that VE and BO elicited stronger parasympathetic responses (see Figure 7 for details).

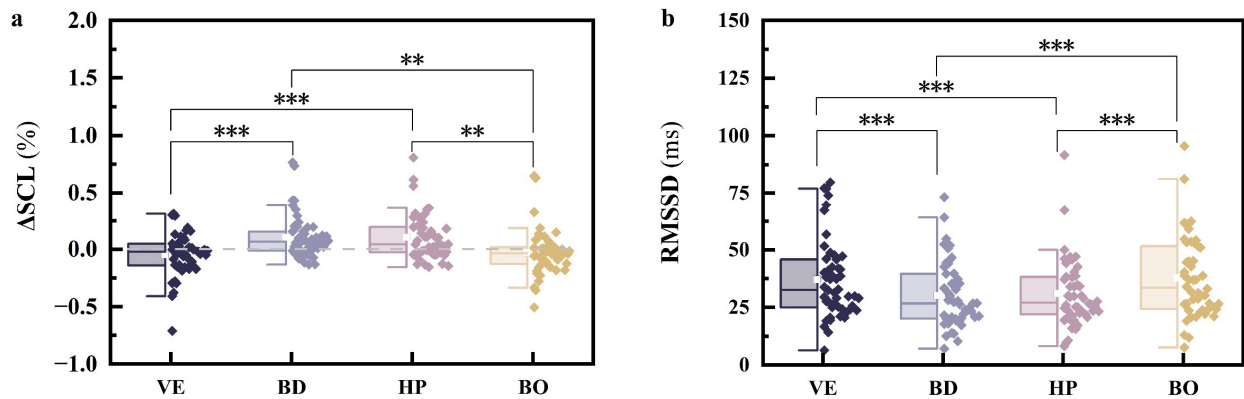


Figure 7. Comparison of physiological responses across four scene typologies. (a) Δ SCL (%) from resting baseline to exposure. (b) RMSSD (ms). Typologies: Vegetation-Enclosed (VE), Built-Dominant (BD), Hardscape-Plaza (HP), and Blue-Open (BO). Boxes show the median and interquartile range; whiskers show the range; diamonds are individual participants. Colors are used only to distinguish the four scene typologies (VE, BD, HP, and BO) and have no additional meaning. Brackets mark significant pairwise differences. In the figure, asterisks indicate statistical significance (** adjusted $p < 0.01$, *** adjusted $p < 0.001$).

3.3. Subjective Questionnaire

3.3.1. I-PANAS-SF Psychological Questionnaire

The I-PANAS-SF scale (10 items, comprising five positive affect [PA] and five negative affect [NA] subscales) was employed to assess participants' immediate emotional states. Pre-analysis revealed that 'alert' was more readily interpreted within this study's context as arousal sensations such as 'tense' or 'vigilant,' rather than being entirely synonymous with positive affect. This item exhibited relatively weaker consistency than other PA items, potentially compromising the measurement stability of the PA subscale; it was therefore excluded. The remaining PA (four items) and NA (five items) subscales demonstrated good internal consistency, with Cronbach's α values exceeding 0.73 at baseline and in all post-exposure measurement stages. Furthermore, exploratory factor analysis supported a two-factor structure ($KMO \geq 0.61$, Bartlett's sphericity test significant), with the two factors cumulatively explaining approximately 52–59% of variance. The correlation between the PA and NA factors was close to zero, indicating a stable and reliable scale structure.

Regarding the PA dimension, Friedman's test ($k = 5$) indicated an overall difference ($\chi^2(4) = 17.851$, $p < 0.001$; Kendall's $W = 0.089$). Pairwise comparisons were conducted across all five stages (10 pairs) and Holm-adjusted. Wilcoxon's paired comparison results indicated that only the post-exposure PA scores of the VE condition were significantly lower than those of the HP condition ($p < 0.05$), with no significant differences observed between the other conditions.

For the NA dimension, the Friedman test ($k = 5$) yielded highly significant results ($\chi^2(4) = 85.113$, $p < 0.001$; Kendall's $W = 0.426$), indicating that different experiential contexts exerted a significant influence on negative affects. Pairwise comparisons were conducted across all five stages (10 pairs) and Holm-adjusted. Paired comparisons revealed that post-exposure NA scores were significantly reduced across all four scenarios

(VE/BD/HP/BO) compared to baseline ($p < 0.001$), while no significant differences existed between scenario-specific NA scores. This indicates that viewing any type of VR waterfront video substantially diminished participants' negative affects (details in Figure 8).

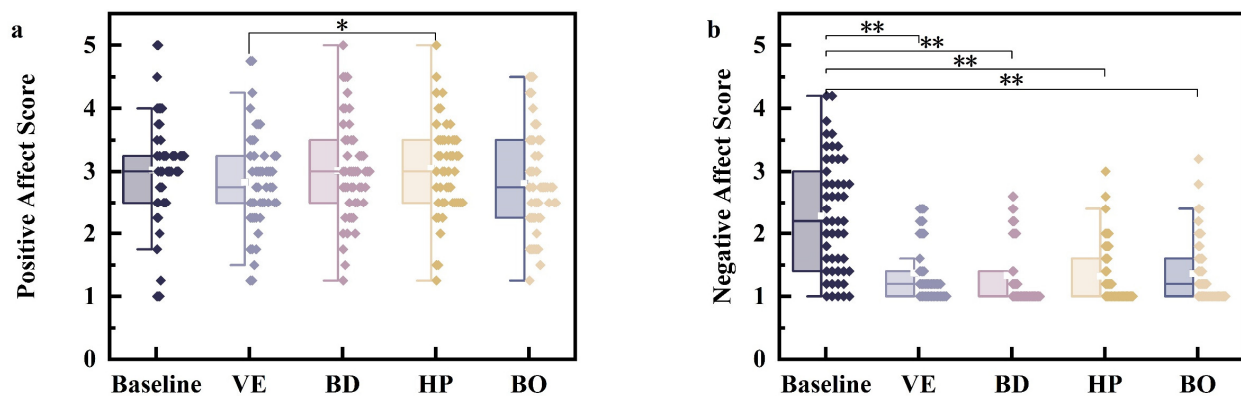


Figure 8. Comparison of subjective affective states across different experimental phases. (a) Positive affect scores and (b) negative affect scores measured at baseline and during exposure to the four scene typologies (VE: Vegetation-Enclosed, BD: Built-Dominant, HP: Hardscape-Plaza, BO: Blue-Open). Boxplots represent the median, interquartile range, and whiskers. Solid points represent individual participant scores. Colors are used only to distinguish the four scene typologies (VE, BD, HP, and BO) and have no additional meaning. Asterisks indicate statistically significant differences compared to the baseline. In the figure, asterisks indicate statistical significance (* adjusted $p < 0.05$, ** adjusted $p < 0.01$,).

Overall, the I-PANAS-SF results indicate that the effect of different waterfront walkway settings on enhancing positive emotions is limited, with significant differences observed only in specific condition comparisons. In contrast, the effect of experiencing various types of settings on alleviating negative emotions is both significant and consistent, with all participants exhibiting a marked reduction in negative emotions following exposure to any scenario.

3.3.2. Landscape SD Method Evaluation Scale

The Landscape SD Method Evaluation Scale comprises landscape dimension (eight items), ecological dimensions (four items), and socio-cultural dimensions (three items). All dimensions demonstrated acceptable internal consistency across different scenarios: Cronbach's α ranged from 0.854 to 0.907 for landscape dimension, 0.680 to 0.784 for ecological dimensions, and 0.534 to 0.767 for the socio-cultural dimension (with slightly lower scores in the socio-cultural dimension for the BD condition). Factor analysis results supported a three-factor structure ($KMO \geq 0.795$, Bartlett's test significant, cumulative variance explained 51–62%). Items exhibited high loadings on their respective factors, supporting construct validity.

For the landscape dimension, Friedman's test ($k = 4$) revealed significant differences in scores between scenarios ($\chi^2(3) = 33.612$, $p < 0.001$, Kendall's $W = 0.224$). Pairwise comparisons using the Holm-adjusted Wilcoxon signed-rank tests indicated significant differences between BD and VE, BD and BO, HP and VE, and HP and BO ($p < 0.01$), while no significant differences were found between other conditions. The overall trend was $HP \approx BD > VE \approx BO$.

The Friedman test ($k = 4$) for the ecological dimension was also significant ($\chi^2(3) = 9.729$, $p < 0.05$, Kendall's $W = 0.065$), though the effect size was modest. Post hoc comparisons revealed that only the HP condition scored significantly higher than the BO condition ($p < 0.05$), with no significant differences between the other conditions.

Consequently, the scoring variations across scenarios within the ecological dimension were limited, with the HP condition performing marginally better than the others.

On the social–humanistic dimension, Friedman test ($k = 4$) results were highly significant ($\chi^2(3) = 47.979$, $p < 0.001$, Kendall's $W = 0.320$). Post hoc comparisons revealed significant differences between BD and VE, BD and BO, HP and VE, and HP and BO ($p < 0.001$), while differences between BD and HP, and VE and BO were not significant. The overall trend indicates that the HP condition $\approx$ BD condition scored highest, while the VE and BO conditions scored relatively lower (HP $\approx$ BD $>$ VE $\approx$ BO). This suggests that scenarios featuring greater public engagement and richer recreational facilities are more favored (details in Figure 9).

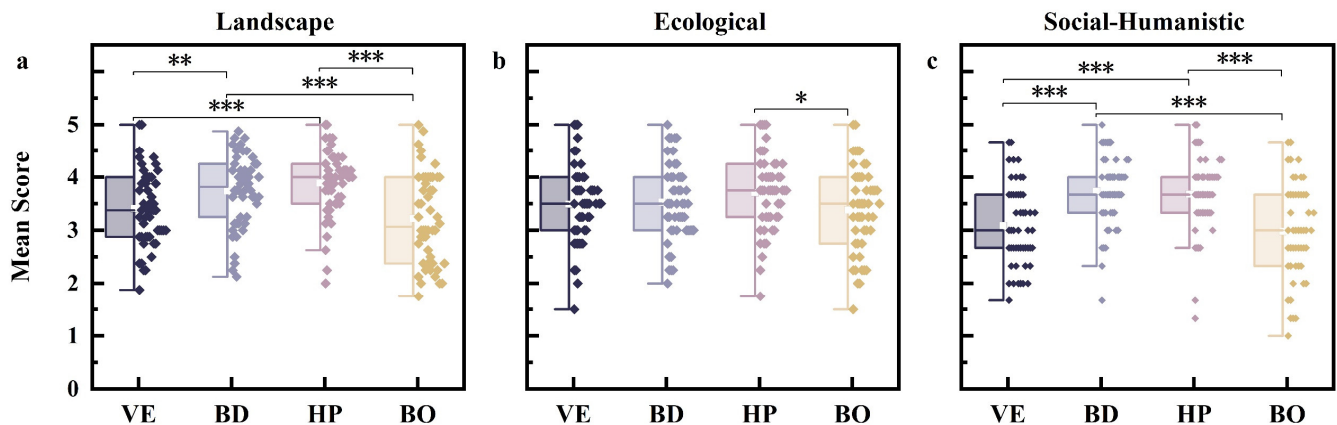


Figure 9. Comparison of subjective environmental quality evaluations across three key dimensions. (a) Landscape quality scores, (b) ecological quality scores, and (c) social–humanistic atmosphere scores across the four scene typologies (VE: Vegetation-Enclosed, BD: Built-Dominant, HP: Hardscape-Plaza, BO: Blue-Open). The boxplots display the median, interquartile range, and whiskers. Solid diamond points represent individual participant ratings. Colors are used only to distinguish the four scene typologies (VE, BD, HP, and BO) and have no additional meaning. Asterisks indicate statistically significant differences between scene types. In the figure, asterisks indicate statistical significance (* adjusted $p < 0.05$, ** adjusted $p < 0.01$, *** adjusted $p < 0.001$).

4. Discussion

4.1. Differences in Physiological Responses Elicited by Distinct Landscape Types

Under fixed-speed, fixed-duration VR exposure, our data suggest differences in autonomic regulation by scene typology (Figure 6). RMSSD increased from baseline in VE and BO, consistent with stronger parasympathetic regulation [36,65,66]. BD and HP showed higher SCL alongside reduced RMSSD, a pattern consistent with sustained sympathetic arousal [36].

Across all typologies, participants' electromyographic (iEMG) and range of respiratory rate (RRR) increased from baseline to exposure. Because participants remained seated, these increases are unlikely to be driven by gross physical activity and may reflect attentional load, non-specific tension, or minor postural adjustments. This can be tested by adding posture tracking or a light walking condition to separate visual attention from visual–motor coupling.

4.2. Analyzing the Relationship Between Visual Composition and Physiological Mechanisms

Linking the quantified visual composition to physiology, we found that typologies differed in GVI and SKVI, with descriptive separation in BVI and HVI (Figure 5). Although BVI and HVI were not significant overall ($p > 0.05$), BD tended to show higher BVI and HP tended to show higher HVI, consistent with the typology labels. The directionality

of these visual contrasts coincided with the type differences observed in RMSSD and SCL (Figure 6).

One possible explanation lies in the prevalence of low spatial frequency elements and fractal structures in natural scenes, which can induce a ‘soft fascination’ effect. This effect reduces cognitive load, captures passive attention, induces a state of relaxation, and activates the parasympathetic nervous system [14]. In contrast, the high-frequency scenes and regular geometry of artificially constructed scenes may increase visual search and elevate attentional load [67–69]. The high-frequency scenes and regular geometric patterns in artificially constructed scenes may increase visual search demands and elevate attentional load, leading to sustained sympathetic nervous system activation that hinders deep relaxation.

Building on the legibility and ‘serial vision’ perspectives introduced in the Introduction, the typology contrasts observed here can be interpreted as differences in how easily a dynamic streetscape can be organized during movement. Typologies with higher GVI/WVI and SKVI (VE/BO) provide more salient blue–green cues and openness that may support scene organization and reduce visual complexity, whereas relatively higher HVI/BVI (BD/HP) reflect stronger hard-edge and built dominance that may increase visual load, aligning with the divergent RMSSD and SCL patterns across typologies [57–59].

In our data, typologies with higher natural visibility tended to show higher RMSSD and lower SCL during exposure, consistent with greater parasympathetic engagement. Together, the results suggest that increasing visible vegetation or water and reducing extensive hardscape or building dominance may support autonomic relaxation under dynamic viewing.

4.3. Recovery Effects in Immersive Dynamic Environments

We used 360° panoramic VR video to provide continuous first-person visual input along a waterfront walkway. This stimulation preserves the continuous visual flow characteristics such as scene progression and perspective shifts, which are typically absent in static images. The existing research indicates that dynamic visual stimuli and visual-proprioceptive inconsistencies in VR can modulate autonomic nervous system indicators such as heart rate and HRV [70,71].

In the past three years, comparative studies have increasingly adopted dynamic roaming or transition-based VR paradigms to more closely approximate real-world movement under controlled exposure conditions and to test short-term psychological and physiological restoration effects. For example, Chen et al. presented 360-degree scenes in an immersive CAVE system to simulate transitions between adjacent built and natural environments, and found that transitioning from built to natural settings significantly reduced negative affect and anxiety, accompanied by observable physiological responses [21]. In a randomized acute cross-over study conducted in a real-life group setting, Kumpulainen et al. reported that VR nature exposure increased heart rate variability and reduced heart rate compared with a non-VR reference condition, suggesting enhanced parasympathetic regulation [72]. A recent systematic review likewise concluded that incorporating natural elements into immersive VR environments is consistently associated with improvements in stress-related outcomes, while also emphasizing that dynamic VR research still requires greater standardization in exposure formats and physiological reporting [73]. These recent comparative studies suggest that, under minutes-scale immersive and dynamic or transition-based virtual exposures, autonomic markers such as HRV and electrodermal activity can show measurable changes. These findings provide convergent external evidence for interpreting the typology-level differences in RMSSD and SCL observed in this study. However, recent reviews also emphasize substantial heterogeneity across dynamic

VR studies, driven by differences in immersion levels, exposure duration, media type, and physiological reporting, which limits cross-study comparability and design translation [73]. In this context, our fixed-dose first-person walk-through protocol, combined with explicit visual composition quantification, helps reduce protocol-driven variability and provides interpretable evidence that can be more readily linked to waterfront design and retrofit decisions.

In this study, both the inter-muscle electromyography (iEMG) and respiratory rate range (RRR) increased from baseline to exposure across all typologies. By contrast, HRV and SCL varied by typology. These findings align with the existing research: for instance, one study observed a significant increase in RMSSD when participants were immersed in VR environments rich in natural elements [74], while another noted a marked reduction in SCL within biophilic design scenarios incorporating natural elements [75]. Both point towards a trend of decreased sympathetic activity and enhanced relaxation responses within natural settings.

Together, these results suggest that autonomic shifts associated with natural visual content can occur even under seated, non-exercise viewing conditions. This supports the relevance of SRT and ART under dynamic viewing, while the present evidence remains limited to short-term, visual-only exposure [20].

Therefore, this study not only validates the restorative effects of natural environments but also suggests that even passive viewing of dynamic natural content within VR can activate physiological restorative responses comparable to those in real-world settings. Consistent with the existing research, virtual nature exposure improves mood and reduces stress/physiological arousal levels, indicating its restorative potential [76]. Future research on SRT and ART should focus more on the impact of environmental dynamism on restorative mechanisms, particularly the role of dynamic perception in virtual or semi-immersive experiences.

4.4. The Phenomenon of Subjective Preferences Being out of Step with Physiological Responses

It is noteworthy that, in this study, participants' subjective environmental preferences and emotional improvements did not entirely correspond with the relaxation levels indicated by their physiological responses. Following a brief virtual waterfront stroll visual experience, all scenarios reduced participants' negative emotions, with participants even reporting a slight subjective sense of relaxation in the BD and HP settings. However, only scenes rich in natural elements induced a significant autonomic nervous system calming effect, while physiological tension remained markedly present in artificial settings. This indicates that subjective emotional improvement does not fully reflect the degree of physiological stress recovery.

Several mechanisms may explain this divergence. Self-reported affect can shift rapidly after brief exposure and may be influenced by general engagement or novelty during VR sessions, whereas autonomic indices (e.g., SCL and RMSSD) reflect partly automatic regulation that can remain sensitive to typology-specific visual load and may require longer exposure and/or post-exposure windows to show full recovery. Moreover, subjective ratings capture conscious appraisal, while physiological measures index stress-related regulation that may decouple from perceived relaxation under short, visually driven exposure. This pattern reinforces the methodological value of multimodal designs and has been noted in recent evidence syntheses of VR-based interventions and VR nature exposure, which emphasize heterogeneity across protocols and the importance of jointly interpreting psychological and physiological endpoints [33]. Similar phenomena have been reported in prior research: for instance, studies found that viewing virtual urban streets could also slightly alleviate stress, yet the restorative benefits of virtual green spaces and

blue spaces far exceeded those of urban environments [66]. This serves as a reminder that individuals' subjective perceptions of relaxation within an environment do not always fully reflect the degree of physiological stress alleviation experienced. Consequently, reliance solely on subjective reports may underestimate or misjudge an environment's true restorative effects, necessitating a comprehensive assessment incorporating objective physiological indicators [36]. Multimodal evaluation methods aid in comprehensively capturing restorative effects, circumventing the limitations inherent in relying on either subjective or objective metrics alone.

This subjective–physiological discrepancy also has practical implications for participatory design. When survey or focus-group ratings are driven mainly by aesthetic appeal or interest, they may overestimate restorative comfort even if autonomic indicators suggest sustained physiological tension. Integrating subjective feedback with objective indicators, or design proxies linked to them, can help avoid prioritizing environments that are well liked but do not support short-term autonomic relaxation. In addition, given the brief exposure duration (50 s per block), some physiological changes may reflect immediate autonomic reactivity rather than complete recovery trajectories; this methodological boundary is further discussed in Section 4.6.

4.5. Implications for Landscape Design and Public Health

At the landscape design level, our results suggest that visible blue–green composition along waterfront walkways is linked to autonomic relaxation during dynamic viewing. The findings of this study confirm the objective value of vegetation and water bodies as restorative elements, demonstrating their ability to significantly reduce physiological stress not only in static visual perception but also in dynamic visual perception [65]. This implies that in environmental health practices, enhancing GVI and WVI can be achieved by increasing green coverage, enriching plant stratification, and expanding waterfront views, thereby creating environments that support stress reduction and psychophysiological relaxation [77]. For hard surface areas like BD and HP, visual stress can be reduced by incorporating bio-affinity elements. Specific methods include introducing natural biomimetic forms or fractal textures into paving patterns, adding vertical greening to building facades, or installing water-friendly platforms [78]. This aligns with internationally advocated biophilic design principles: integrating natural features into artificial spaces to improve health and well-being [77].

Simultaneously, VR technology serves as a new tool in the planning and design phase, enabling us to conduct evidence-based optimization of design proposals prior to construction. Furthermore, VR proves highly effective in assessing the impact of street landscape renovations on public sentiment and comfort levels [79].

4.6. Research Limitations and Future Prospects

This study evaluated the psychological and physiological responses of individuals to different types of waterfront promenades under controlled seated conditions and brief VR exposure primarily focused on visual perception. However, certain limitations within the research should be noted.

The direction of change observed in RMSSD and SCL in this study generally aligns with existing field research, providing some confirmation of VR's effectiveness as a tool for environmental psychology studies [20]. However, its effects primarily manifest through the visual dimension, while other sensory dimensions remain unsimulated. Therefore, it cannot fully replace real-world environmental exposure. Future work can test the ecological validity by comparing the same routes in VR and in situ walking, and/or by adding controlled auditory and microclimatic cues to quantify how multisensory input

alters the effect magnitude. Additionally, this study employed only the proportion of visual elements as the raw data for k-means clustering, without incorporating dimensions such as soundscapes, spatial scale, or crowd density. Another limitation is that pixel-level ground-truth labels were not available for the panoramic frames, which prevented a dataset-specific quantitative evaluation of segmentation accuracy. Future work could annotate a subset of frames to compute metrics such as mean IoU and quantify how segmentation uncertainty around reflective water surfaces propagates to GVI and WVI estimates. Future research may integrate multi-source objective data into clustering to expand scene representation. Moreover, incorporating individual-difference measures, such as baseline stress level or environmental preference traits, may help explain heterogeneity in restorative responses across participants. Concurrently, neurobehavioral indicators such as electroencephalography (EEG) and eye-tracking can be incorporated to broaden the measurement dimensions, which could deepen investigations into human–environment interaction mechanisms.

Given that the sample primarily consisted of young students and the VR exposure duration was brief (50 s per block), the findings primarily reflect immediate autonomic responses during the exposure window rather than full recovery trajectories that are typically characterized over longer observation periods. Therefore, caution is warranted when extrapolating findings to broader contexts. Future research should extend both the exposure duration and the post-exposure observation time and systematically manipulate the exposure dose to test the dose–response patterns and cumulative effects, thereby improving generalizability in larger and more representative samples.

5. Conclusions

This study assessed short-term psychophysiological responses to first-person dynamic viewing of urban waterfront walkways in VR. Under fixed-duration exposure, typologies with higher visible vegetation and water (VE/BO) were associated with a more relaxed autonomic pattern (higher RMSSD and lower SCL), whereas more built- and hardscape-dominant typologies (BD/HP) showed the opposite tendency. Although self-reported mood improved across all scenarios, the autonomic responses differed by typology, suggesting that subjective reports alone may not fully capture the underlying stress-related physiology.

Methodologically, we integrate semantic segmentation-based visual quantification (GVI/WVI/SKVI/HVI/BVI), typology-based scene comparison, and multimodal measures within a controlled VR protocol, providing a reproducible workflow for evaluating waterfront visual environments. In practice, the findings suggest that design moves that increase visible vegetation and water frontage (higher GVI/WVI) and limit long segments dominated by hard surfaces or building edges (higher HVI/BVI) are more likely to support autonomic relaxation under brief, first-person dynamic viewing.

Beyond these findings, this study advances the field in three ways. First, it provides a dose-controlled first-person dynamic VR walk-through paradigm that improves reproducibility in short-term restorative exposure research. Second, it links interpretable view-based visual composition to multimodal psychophysiological outcomes, offering a design-oriented evidence bridge between what pedestrians see and how they respond. Third, by identifying consistent typology-level patterns under a fixed exposure dose, it supports more comparable cross-study interpretation and informs performance-oriented planning and retrofit of waterfront promenades.

Although the sample structure of this study was relatively homogeneous and the exposure duration limited, warranting further validation of findings across broader populations and contexts, it nonetheless expands the methodological boundaries of restorative environ-

ment research. Moreover, it provides scientifically grounded insights of considerable value for the planning and intervention of urban blue–green spaces.

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