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RESEARCH ARTICLE

Modulatory effects of the landscape sequences on pedestrians emotional states using EEG

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Abstract This study aimed to investigate the impact of specific landscape elements on pedestrians' emotional experiences during walking. During the study, footages were recorded by participants while walking to obtain real-time visual element data, including greenery, building and road visibility. And electroencephalogram (EEG) indicators of β/α, $(\alpha+\theta)/\beta$, θ/β and θ/α ratio were collected to represent levels of arousal, fatigue, attention and relaxation. Our findings suggested strong correlations between θ/α ratio with both greenery and road visibility. Conversely, other indicators were primarily influenced by greenery and building visibility. Regarding the combined impact of elements, the most positive emotions were observed when green visibility exceeded 51%. However, the peak alertness was achieved with building visibility between 5.2% and 31%. The lowest fatigue and the highest attention level were recorded under building visibility less than 5.2%, and the highest level of relaxation occurred with road visibility less than 10%. In terms of the influence of time, the entire walking process could be delineated by the five and 8 min marks, classified into novelty, adaptation and sustained phase based on the patterns of emotional changes observed in the participants. Consequently, the visual elements and their combinations, and duration play regulatory roles in pedestrians' emotional experiences.

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1. Introduction

Walking is undervalued in the overall transport system despite its ability to reduce congestion, conserve energy, be free from pollution, and socially equitable. It should be recognized not just as a utilitarian mode of transportation but also for its social and recreational benefits that enhance the comfort and appeal of daily journeys (Hassan et al., 2021). The emotional recovery effects of walking environments on urban residents are gaining attention, with the restorative impacts of visual landscape elements and form indices in static walking spaces broadly confirmed (Zhang et al., 2024a; Zhao et al., 2023). However, as pedestrians move, the scenes they experience change over time. While walkability is closely related to temporal perception, this dynamic physical experience is less frequently considered than other temporal arts (Hassan et al., 2021), leaving the effectiveness of visual landscape sequence designs attuned to dynamic experiences yet to be explored. Mobile physiological testing devices and semantic image segmentation technology are used to extract physiological responses and visual landscape element proportions during walking (Aspinall et al., 2013; Zhang et al., 2024b), enabling further research into how primary element types, combinations, and duration influence emotional recovery in the walking process, thus providing a basis for urban landscape sequence design.

1.1. Impact of visual landscape in public spaces on pedestrian behavior, emotions, and health

The 21st century presents substantial challenges for the built environment, extending beyond the mere physical redesign of spaces to encompass the vital task of creating healthier public spaces that encourage walking and social interaction. Thoughtfully designed spaces hold the potential for positive impacts. Research has demonstrated that the visual elements of public spaces can influence public behavior, psychology, and health (Bai et al., 2022a, 2022b; Kim et al., 2019; Li et al., 2021; Wu et al., 2021; Ye et al., 2022). Zumelzu et al. (2022) indicated that design elements of streets, such as connectivity, sidewalk width, types of vegetation, and building facades, significantly affect the walkability of streets. Similarly, Song et al. (2020) found that factors such as water features, length of pedestrian pathways, food establishments, footpath length, and waterfront length-to-perimeter ratio influence the frequency of urban park visits. Li et al., 2024 discovered that urban greenery and street accessibility significantly increase pedestrians' willingness to walk and that a balanced distribution of sidewalk elements can further enhance their psychological restoration capabilities. Wang and Huang (2024) discovered that while the presence of only rest seats or greenery did not significantly affect the number of people staying, the combination of both greatly increased the number of visitors remaining in the area. Kong et al. (2022) found that emotions positively correlate with park size and the average area of water bodies while negatively correlated with large areas of impervious surfaces, as analyzed through social media data. Ye et al. (2022) highlighted the importance of visual media attributes in influencing visitors' positive emotions. Additionally, Dennis and James (2017) concluded that compared to urban green spaces, domestic gardens had a greater impact on health.

The campus environment of universities, as the daily living and activity space for students and faculty members, plays an equally important role in students' physical and psychological well-being. Browning and Rigolon (2019) reviewed the relationship between academic performance, green space types, and school-to-green area distance, revealing significant positive outcomes, particularly within a 2000-m radius of schools with green coverage. Also, Liu et al. (2018) established a significant correlation between perceived naturalness and self-rated restoration, encompassing emotional, physiological, cognitive, and behavioral responses. Foellmer et al. (2021) found that academic green spaces alleviate fatigue from prolonged attention, enhance mental health, evoke positive emotions like happiness and vitality, and foster a sense of social belonging that supports academic success.

It is notable that most of the current research primarily employs methods such as subjective questionnaires, government statistical data, and social media data. However, these approaches predominantly involve an overall assessment of experiences within static scenarios or over a specific period, struggling to capture the dynamic experiences within sequential contexts. Consequently, studies focusing on real-time feedback and providing guidance for the design of sequential experiences have limited applicability.

1.2. Physiological indicators of emotion: skin conductance levels, electrocardiogram, electroencephalogram

In these studies, physiological factors, such as skin conductance levels (SCLs), Heart Rate, and electroencephalogram (EEG), have been demonstrated as effective measures for evaluation. Virtual reality (VR) demonstrated that, after a 10-min restorative experiment, courtyards with grass or trees significantly reduced skin conductance levels compared to those without vegetation (Huang et al., 2020). Similarly, Zhang et al. (2021) observed participants' emotional responses to urban street scenes through VR experiments and found that the proportion of roads is significantly positively correlated with skin conductance response amplitude (SCR.Amp).

In addition to SCLs, heart rate is considered a criterion for emotion evaluation, with walking in urban parks resulting in lower heart rates than walking on streets. Song et al. (2013) discovered that during winter walks through urban parks, heart rates were significantly lower, and the natural logarithm of the high-frequency component of heart rate variability (HRV) was significantly higher compared to walks through city areas, with subjective survey results consistently indicating that walking in urban parks can improve mood and reduce negative emotions and anxiety. Similarly, Song et al. (2014) also obtained consistent results in their study on young males' physiological and psychological responses during spring-time walks in urban parks. Furthermore, researchers have proposed an algorithm to estimate human perception by collecting scores from volunteers based on thousands of street view images

(Zhang et al., 2018). Walford et al. (2017) selected 44 elderly individuals to watch recorded walking routes while measuring their heart rates and conducting surveys to analyze the distribution characteristics and interrelationships among environmental, physiological, and psychological factors.

EEG signals, facilitated by computer-aided technologies, have diverse applications, including diagnosis of neurological disorders, emotion recognition, and sleep stage classification (Khosla et al., 2020). The hypothesis regarding the correlation between urban green space exposure and mental health has been supported by analyzing participants' EEG signals and alpha asymmetry values (Olszewska-Guizzo et al., 2020). Zou et al. (2021) found that lower buildings and urban environments with green vegetation are more effective in alleviating stress, as indicated by an increase in the difference between alpha and beta brain waves, representing stress recovery. However, despite multiple attempts to discuss the correlation between EEG signals and visual images, a definitive conclusion has not yet been reached.

Notably, visual simulations of natural scenes have been observed to elicit higher levels of α, β, δ, θ and γ waves compared to urban traffic photographs (Jiang et al., 2019). Conversely, another group of researchers found no significant difference in participants' EEG when exposed to different visual types (Gao et al., 2019). Deng et al. (2020) conducted an analysis of variance (ANOVA) of the average values of α, β and θ waves, revealing significant differences between different groups over time, but no significant difference within the groups.

1.3. Exploration of pedestrian mobile cognition in urban environments

Cognitive neuroscience studies in humans have enabled decades of impactful discoveries but have primarily been limited to recording the brain activity of immobile participants in a laboratory setting (Stangl et al., 2023). However, various behaviors have been found to have different effects on EEG (Zink et al., 2016). Lin et al. (2020) found that emotional responses vary across different stages of movement, with meditation and valence showing higher indicator values during walking compared to sitting, indicating an improved ability to manage stress. Wang et al. (2020) also observed increased activity in alpha waves during movement in the natural environment. Therefore, there is a need for a study that focuses on the continuous responses of visual landscapes and the design of architectural sequences (Jin et al., 2021). The use of wearable sensors and mobile devices for ubiquitous, continuous, and personal monitoring has expanded beyond clinical research, and could be integrated into urban studies as a tool to understand and assess human psychological responses, helping to improve design strategies for urban environments (Mavros et al., 2016). A mobile EEG study comparing 25-min walks through an urban shopping street, a green pathway, and a busy commercial street in Edinburgh showed that participants experienced lower frustration, engagement, and arousal, but higher engagement when moving out of it (Aspinall et al., 2013). Tilley et al. (2017) conducted EEG tests on elderly individuals walking through urban paths and found that walking along busy streets led to feelings of depression, while passing through areas with flowers or green spaces increased excitement and engagement indicators, improving negative emotions. Jones et al. (2021) found walking in a natural or pleasant urban environment is beneficial to mood, and that visiting natural environments further enhances restorative experiences, with the benefits of being in natural settings consistently realized over time. However, most are qualitative studies and trend analyses of the overall characteristics of walking routes, with a lack of research on the quantitative relationship between landscape element proportions, time, and the dynamic perceptions of pedestrians.

The current study addressed the following question through on-site visual experience experiments conducted in outdoor spaces. How do single landscape elements, combinations of landscape elements, and walking duration affect EEG signals that reflect pedestrians' emotions? This paper centers on the internal landscape of the Huazhong University of Science and Technology (HUST) campus in Wuhan, China, for its high green coverage and residential-like environment (see Fig. 1). And to investigate the queries, a correlation analysis method was used to determine the relationship between emotions and the visibility of visual elements. In addition, the study assessed the effects of combinations and duration on pedestrians' emotions as observed through EEG signals. These findings will provide references for the design of walking space landscape sequences, contributing to optimizing pedestrian experiences in campus public areas and promoting the development of refined design approaches.

2. Methods

The experiment comprises three steps: 1) The initial stage involving participants' walking and data collection; 2) The intermediate phase of data extraction and processing; 3) The final stage of data analysis.

2.1. Data collection

The experiment selected 24 groups of participants, who were divided into eight teams, walking towards each other

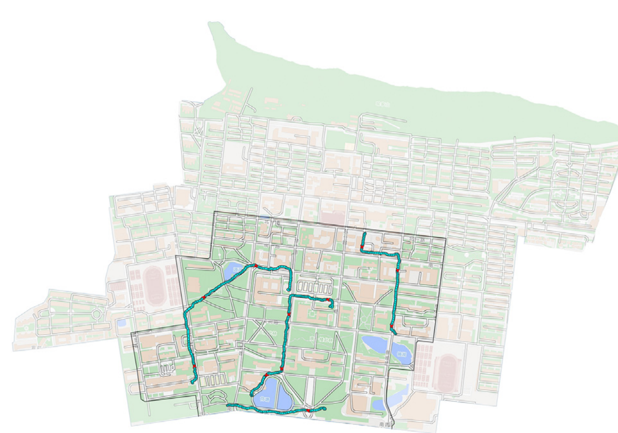


Fig. 1 The selected experimental site.

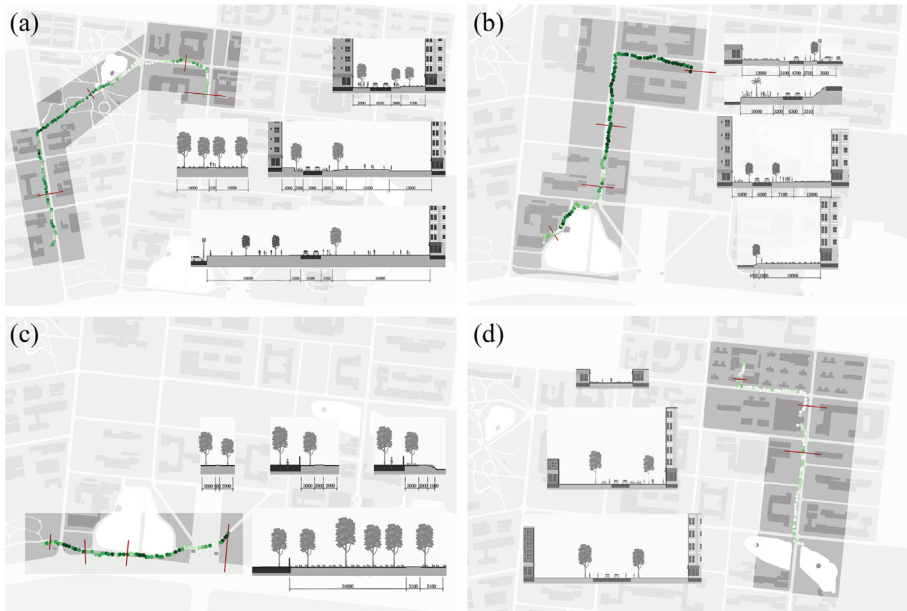


Fig. 2 The layout, distribution of greenery visibility and road cross-section of four routes. (a) From West Building 12 to the Library; (b) from South Building 4 to the History Museum; (c) from South Building 4 to South Gate 1; (d) from Zuiwan Pavilion to Wutong Yu.

from both ends of four routes on the campus, as illustrated in Fig. 2, on 24th and 25th May 2022. Each route had a walking duration ranging from 6 to approximately 10 min and features varying landscape sequences. This design allowed for the study of the impact of different landscape elements on walkers.

Participants in the experiment comprised 24 senior students from the School of Architecture and Urban Planning. To minimize potential confounding factors, the influence of age and major was excluded. The experimental setup involved the use of wireless physiological recorders connected by various electrode pads and a Garmin GPS handheld device, which they wore as they traversed designated routes. Simultaneously, portable cameras were used to record real-time visual footage of their walking experiences. A team member carried a laptop to receive real-time physiological data transmitted by recorders. This experimental setup and procedure is depicted in Fig. 3.

2.2. Data extraction and processing

Further processing was performed on the data obtained from the experiment. The EEG data collected by the physiological instrument were imported into Biopac platform for analysis and subsequent exportation. EEG signals were divided into five wavebands based on frequency: α (8–13 Hz), β (13–30 Hz), θ (4–7 Hz), δ (0.5–3 Hz), γ (31–50 Hz). Ratio indices of α/β, θ/α, θ/β, and $(\alpha+\theta)/\beta$ were adopted to compare normal and fatigue states (Eoh et al., 2005), and wavelet pocket decomposition (WPD) was used to obtain energy levels in each brain wave. And four mental fatigue indices were employed for subsequently calculation for the following reasons.

The β/α ratio has been recognized in previous studies as an effective value for visual evaluation (Hsu et al., 2013). In the collected EEG data, the β/α ratio signifies the arousal level (Suh et al., 2018), while $(\alpha+\theta)/\beta$ ratio denotes fatigue level or the subjects' activation (Brookhuis et al., 1993). A study focused on the relation between physiological parameters and drivers' status noted an increase in the $(\alpha+\theta)/\beta$ ratio as driving periods extended, suggesting escalating fatigue levels. Conversely, the β/α ratio demonstrated a declining trend with prolonged driving, pointing to decreasing arousal levels in participants (Eoh et al., 2005).

The θ/β ratio was initially introduced as an EEG marker for attention deficit and hyperactivity disorder (ADHD) diagnosis and attentional control investigation (Lubar, 1991). Subsequent studies focused on healthy participants found the θ/β ratio to be negatively correlated with self-reported trait attentional control (Clarke et al., 2019). Based on existing scientific research, the θ/β ratio was adopted in this study to describe the participants' attention level. The θ/α ratio is also used to assess relaxation, as it has been shown to be different for attention deficit disorder (ADD) or ADHD patients (Clarke et al., 2002).

The α/θ protocol is known as the most famous neurofeedback method for stress reduction, and as a method for inducing an enhanced θ/α rate (Chen and Kang, 2023; Marzbani et al., 2016). A multiple linear regression analysis has indicated that the θ/α ratio is negatively related to vigilance level (Matousek et al., 1983). Researchers found that the θ/α ratio decreased in all lobes of the brain, indicating the relaxed state of subjects when evaluating the cognitive behaviors of a group of young healthy subjects (Nagendra et al., 2015).

Figure 2 shows the participants recording first-person videos while walking. Keyframes were extracted from the videos corresponding to physiological data every 5 s for visibility analysis.

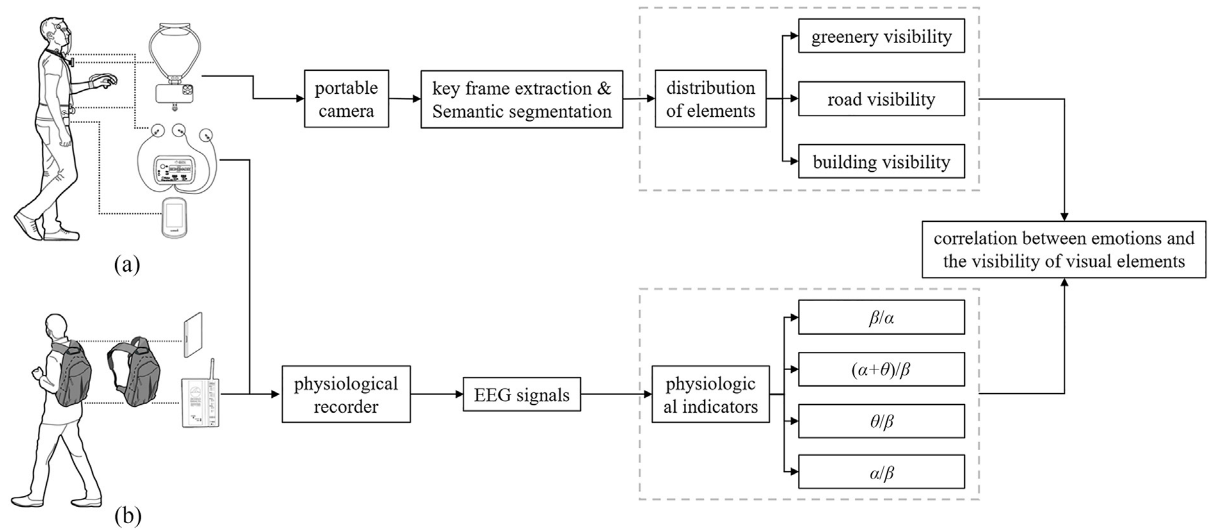


Fig. 3 The experiment procedure—(a) carries electrode patches, a brainwave collector, a mobile phone, and a GPS, while (b) carries the collector host and a laptop.

A visual image semantic segmentation tool based on deep learning fully convolutional network (FCN), developed by the High-Performance Spatial Intelligence Computing Laboratory (HPSCIL) at the China University of Geosciences, was applied in this study to segment street view images into 150 types of objects (Yao et al., 2019). Proportions of various elements within the scenes were obtained, including sky, road, grass, soil, buildings, windows, trees, water, and more. Based on the experiential path space analysis, elements with the same expressiveness are combined and categorized according to the principles of visual recognition in landscape spaces. The values were then summed by category to derive the four main elements—sky, greenery (tree, grass, plant, water), buildings (wall, buildings), and roads (road, sidewalk, earth, field), as shown in Fig. 4. This procedure provided real-time visibility data throughout the entire walking process.

To enhance the visual characteristics of the scenes, the four visibility elements were further processed. One of the analysis elements introduced is the natural-artificial ratio, which was calculated as (sky + greenery)/(building + road). This ratio was used to highlight the impact of different types of visual elements on participants.

Once the start and end time were aligned, a continuous physiological and visual dataset with an interval of 5 s is obtained. This dataset includes the EEG indices, such as β/α, $(\alpha+\theta)/\beta$, θ/β and θ/α ratio, as well as proportions of visual elements including sky visibility, greenery visibility, buildings visibility, roads visibility and natural-artificial ratio, along with the relevant time of the entire walking process, as shown in Table 1. However, the visibility of sky was restricted to be mostly below 5%, due to the excessively high vegetation coverage along the chosen routes. Consequently, the analysis of sky visibility was omitted in subsequent analysis. A total of 2265 lines of real-time physiological visual data were extracted and sorted for further analysis.

2.3. Determination of visual sequence indicators related to EEG

The variables were analyzed for Pearson correlation using SPSS to examine the relationship between EEG indices, visibility of landscape elements, and walking duration along a route through correlation analysis. The application of Pearson correlation analysis was based on the following conditions: 1) both visual and physiological indicators were continuous variables derived from the same individuals; 2) scatter plots demonstrated a discernible linear relationship between the variables under examination; 3) box plots showed that the number of outliers in the variables was less than 1% of the total sample size; 4) normality of the data

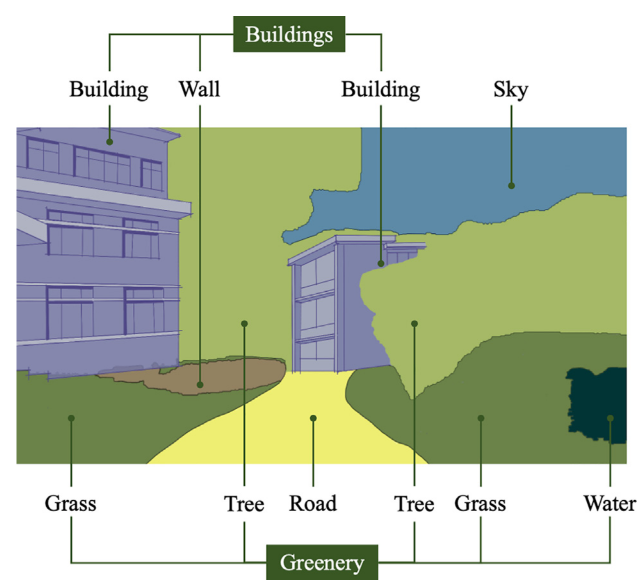
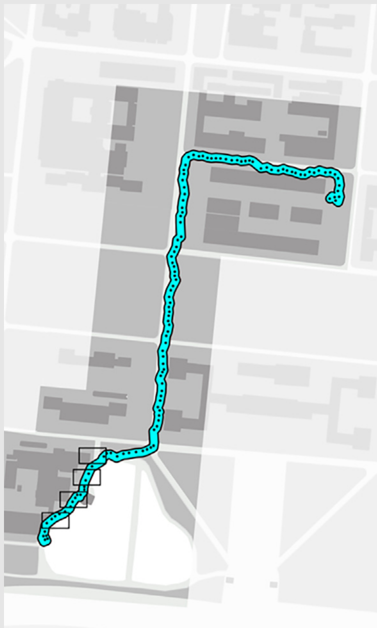
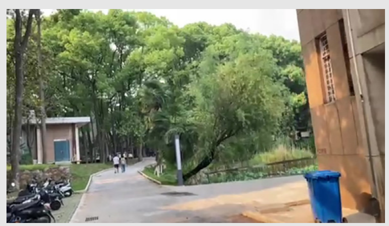
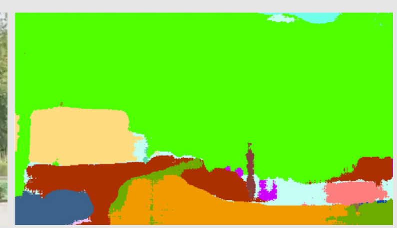


Fig. 4 Schematic of visual elements in one scene during walking.

Table 1 Data on landscape elements and EEG indicators of pedestrian routes.

	Captured image	Segmentation image	Greenery visibility	Sky visibility	Building visibility	Road visibility	β/α	$(\alpha+\theta)/\beta$	θ/β	θ/α
			43.13%	12.92%	37.77%	5.86%	2.92	0.49	0.16	0.45
			29.09%	4.82%	50.35%	10.95%	10.45	0.31	0.22	2.27
			27.11%	5.75%	8.60%	7.26%	1.50	1.51	0.84	1.26
			73.18%	0.53%	7.60%	11.00%	14.34	1.52	1.45	20.75

was assessed using Q–Q plots, and it was concluded that the variables approximated a normal distribution. Hence, correlation analysis was conducted to study the relationship between the primary and subjective variables, aiming to identify visual elements that influence participants' experiences. And when analyzing the correlation between walking time and physiological data, data from different participants with same walking durations were selected for average value calculation. This approach aimed to obtain design indicators for visual landscape sequences that affect EEG signals.

2.4. Assessment of EEG difference among various visual element combinations

To simplify the analysis of the joint effects under different levels of visual elements, the visibility levels of greenery, building, and road were categorized into two tiers: high and low. Based on the results of the single element correlation analysis, significantly correlated elements were selected for combination analysis to examine their joint effects. Therefore, a total of eight combinations composed of greenery and building visibility, as well as greenery and road visibility were used for ANOVA analysis using SPSS. In the process of categorization, the adequacy of sample sizes after considering combinations of pertinent influencing factors was assessed. In line with prior research by Chen and Kang (2023), which posited that natural sounds can enhance social interactions in urban parks, the criterion for categorization was established to ensure a minimum sample size of no less than 10, as depicted in Table 2. The sample sizes under various combined conditions exceeded 50, as shown in Table 3.

2.5. Analysis of influence of time on EEG in different combinations

Based on the correlation analysis of single visual elements,a notable correlation was observed between time and the studied physiological indicators. Consequently, an additional analysis was conducted to explore the combined impact of time and visual element combinations, providing insights into the effect of scenes at different positions within the sequence on participants. Li and Kang (2019) found a relatively strong relationship between physiological parameters measured in the first minute and subjective evaluation results. Taking 60 s as a unit, the values of EEG indices were computed for different visual element combinations. Subsequently, points with insufficient cases were excluded, and an analysis of variances was performed, followed by a qualitative analysis using line graphs. The sample sizes per minute were detailed in Table 3, with datasets containing fewer

Table 2 The categorizing criteria of three levels for four visibilities.

Type	Greenery visibility	Building visibility	Road visibility
Low	0–51%	0–5.2%	0–10%
High	51%–95%	5.2%–55%	10%–50%

Table 3 Numbers of minute-wise EEG data samples collected across greenery and road visibility combinations.

Combination mode	LG + LR (low greenery, low road)	LG + HR (low greenery, high road)	HG + LR (high greenery, low road)	HG + HR (high greenery, high road)	LG + LB (low greenery, low building)	LG + HB (low greenery, high building)	HG + LB (high greenery, low building)	HG + HB (high greenery, high building)
1 min	30	135	66	45	70	95	56	55
2 min	46	122	69	39	47	121	54	54
3 min	54	131	59	32	69	116	44	47
4 min	50	82	110	34	53	79	49	95
5 min	65	85	111	15	58	92	34	92
6 min	34	91	88	23	47	78	37	74
7 min	40	83	67	30	47	76	35	62
8 min	27	114	39	14	44	97	26	27
9 min	22	35	47	13	11	46	18	42
10 min	13	20	27	13	8	25	12	28
11 min	11	17	13	4	8	19	10	7
Total	462	845	375	583	392	915	696	262

than 10 samples excluded to mitigate the effects of random variation (Chen et al., 2023). The effective data durations ranged from 1 min to 10 min.

3. Results

3.1. Correlation between single visual element and EEG ratio indices

The results presented in Table 4 revealed significant correlations between the ratios of β/α, $(\alpha+\theta)/\beta$ and θ/β with measures of greenery visibility, building visibility, natural-artificial ratio and duration, while θ/α is related with greenery visibility, road visibility and duration. Specifically, the β/α ratio was positively correlated with the greenery visibility, the natural-artificial ratio and duration, while it demonstrated a negative correlation with building visibility. This suggested that increased greenery visibility, longer walking experience time, larger proportion of natural elements, and lower building visibility were associated with heightened arousal levels as shown in Fig. 5. The $(\alpha+\theta)/\beta$ ratio showed a positive correlation with building visibility, but was negatively related with greenery visibility, the natural-artificial ratio, and duration, suggesting that within the tested range, higher building visibility, lower greenery visibility and the natural-human ratio, and shorter exposure time were associated with higher fatigue levels, as shown in Fig. 5. Furthermore, the θ/β ratio was negatively correlated with greenery visibility, the natural-artificial ratio and duration, and it was positively related with building visibility. These results showed an direct relationship between attention levels and the visibility of greenery and natural elements, as well as duration, and conversely, a inverse relationship between attention levels and buildings visibility within the tested range. Lastly, the θ/α ratio was negatively related to greenery visibility and duration and was positively related to road visibility, indicating that lower proportion of visible greenery, higher proportion of visible roads and shorter time were associated with lower relaxation level, as shown in Fig. 5.

3.2. Effects of combinations of visual elements on EEG ratio indices

3.2.1. Influence of combinations of greenery visibility and building visibility

The results presented in Table 4 indicated significant correlations between the β/α ratio, θ/β ratio and $(\alpha+\theta)/\beta$ with greenery visibility and building visibility. To further investigate these relationships, greenery visibility and building visibility were categorized into two distinct levels, facilitating the analysis of various visual patterns through ANOVA. Subsequent Robust Tests of Equality of Means and ANOVA analysis confirmed that the combined effect of greenery and building visibility significantly influenced all three EEG indices.

Figure 6(a) illustrates the correlation between the greenery-building visibility combinations and their impact on the β/α ratio. The graph shows that combinations featuring high greenery visibility (HG), particularly when paired with high building visibility (HB), were associated with the highest arousal levels. Conversely, a combination of low greenery visibility (LG) corresponded with the lowest β/α ratio, suggesting reduced arousal level. The increase in the proportion of buildings, in cases of low greenery visibility, had no impact on β/α ratio, while in cases of high greenery visibility it resulted in an increase. In contrast, with high greenery visibility, the β/α ratio was positively affected, evidenced by an increase from 15% to 20%, which indicated a heightened arousal state. This trend remained consistent irrespective of the level of building visibility.

Figure 6(b) illustrates the correlation between different combinations of greenery-building visibility and the $(\alpha+\theta)/\beta$ ratio. The results indicated that the lowest fatigue levels, as indicated by the $(\alpha+\theta)/\beta$ ratio, were observed in scenarios with high greenery visibility, particularly when combined with low building visibility (HG + LB). However, the highest level of fatigue were experienced in settings with low greenery visibility and high building visibility (LG + HB). Notably, as building visibility increased in settings with low greenery visibility, a slight increase in the $(\alpha+\theta)/\beta$ ratio was observed. Similarly, in the context of high greenery visibility, the impact of building visibility exhibited a same trend. Specifically, an increase in the greenery visibility resulted in a significant decrease in the $(\alpha+\theta)/\beta$ ratio, regardless of building visibility. With high greenery visibility conditions, this $(\alpha+\theta)/\beta$ ratio underwent a substantial reduction of approximately 10%, indicating a diminished level of fatigue.

Figure 6(c) illustrates the correlation between different combinations of greenery-building visibility and the θ/β ratio. The results demonstrated that scenarios with low greenery and high building visibility (LG + HB) exhibited the highest θ/β ratio, signaling the most attenuated attention levels. Conversely, when greenery visibility was high, the θ/β ratio showed a significant decrease remarkably by 11%. Scenarios with high greenery visibility, particularly when paired with low building visibility (HG + LB), consistently exhibited optimal at attention levels, as evidenced by the lowest θ/β ratio. Notably, transitioning from low to high building visibility in scenarios with both low and high greenery visibility resulted in a slight increase in the θ/β ratio. Regardless of building visibility, an escalation in greenery visibility resulted in a substantial decline in the θ/β ratio, indicating an enhanced attention level.

3.2.2. Influence of combinations of greenery visibility and road visibility

Table 4 shows the correlation between the θ/α ratio and greenery visibility and road visibility. Both visual elements were categorized into two levels to further analyze the combinations of different visual patterns using ANOVA. The Robust Tests of Equality of Means and ANOVA analysis results showed a significant correlation between the combined effect of greenery and road visibility and the θ/α ratio.

Figure 7 depicts the correlation between different combinations of greenery-road visibility and the θ/α ratio. The combination LG + HR (low greenery, high road) produced the highest θ/α ratio, indicating the lowest level of relaxation. Conversely, the combination HG + LR (high greenery, low road) exhibited the highest level of relaxation. In scenarios with high greenery visibility, the overall

Table 4 Correlation between single visual element and EEG indices.

	EEG indices			
	β/α	$(\alpha+\theta)/\beta$	θ/β	θ/α
Greenery visibility	0.186**	−0.095**	−0.086**	−0.063**
Building visibility	−0.055**	0.055**	0.053*	0.035
Road visibility	−0.026	0.010	0.010	0.054*
Natural-artificial ratio	0.102**	−0.073**	−0.069**	−0.073**
Duration	0.239**	−0.442**	−0.443**	−0.356**

relaxation level remained relatively low, with minimal variations in road visibility. However, under conditions of low greenery visibility, an increase in road visibility (from HG + LR to HG + HR) resulted in a significant increase in the θ/α ratio, suggesting a notable reduction in relaxation. Scenarios with greenery visibility exceeding 51% consistently yielded a higher level of relaxation, with an uplift of 5% compared to situations with low greenery visibility.

3.3. Effect of experience duration on EEG ratio indices

3.3.1. Effect of experience duration under various combinations of greenery and building visibility

Based on Table 4, the ratio of β/α representing arousal shows a generally positive correlation with duration, while the ratios of $(\alpha+\theta)/\beta$ and θ/β, which fatigue and attention levels are negatively correlated. Additionally, all combinations passed either Levene's homogeneity of variance test or Welch's test. Consequently, marginal means were calculated for the cross terms of the mode factors, using this data. Broken line plots were then constructed to analyze the changes in EEG ratio over time.

Figures 8–10 illustrate the changes in the β/α, $(\alpha+\theta)/\beta$ and θ/β ratios over time and across various combinations of greenery and building visibility. It is notable that all three types of EEG indices exhibited highly similar patterns in their line graphs, except for the β/α ratio, which exhibited an opposite trend compared to the other two ratios. Based on the overall performance of the data, the entire walking process can be divided into three phases: the novelty phase, the adaptation phase, and the sustained phase. These stages represented the impact of visual elements on participants and the readjustment of pesdestrians. Different types of visuals exhibited distinct influences at different time intervals.

The initial 5 min of the walking process was identified as the novelty phase, characterized by significant fluctuations in the participants' EEG indicators. During this phase, the overall level of the β/α ratio was generally higher under high greenary scenarios compared to low greenery visibility. This suggested a higher level of arousal, indicating an advantage of high greenery conditions in enhancing arousal during this period. Conversely, for $(\alpha+\theta)/\beta$ and θ/β ratios, the situation was completely opposite. Both of them were generally lower compared to low greenery visibility, implying a lower level of fatigue and a higher level of attention under conditions of high greenery visibility. Additionally, higher level of building visibility under high greenery conditions resulted in higher levels of arousal and attention, and lower level of fatigue. Within the novelty phase, the 3rd and 5th minutes served as the extremum, with both arousal and attention levels peaking, while fatigue levels were at their lowest. Moreover, as time progressed, the amplitude of fluctuations in the three EEG indicators followed the order of HG + HB > LG + LB > HG + LB > LG + HB. This pattern suggested that participants exhibited a sensitivity hierarchy to the combinations of visual elements as follows: HG + HB > HG + LB > LG + LB > LG + HB.

The period from the 6th to the 8th minute was referred to as the adaptation phase, during which EEG indicators fluctuated in response to different scenarios. Unlike the novelty phase, no significant and continuous contrast in magnitudes was observed during this period. At this stage, besides the pronounced fluctuations in the EEG indicators under the HG + HB and LG + HB conditions, the changes remained relatively stable under the other two scenarios. For the β/α ratio, under the HG + HB condition, it exhibited a decline amid fluctuations, while in the other three conditions, it underwent a slight fall. By the end of the adaption phase, the β/α ratio under all scenrios converged to similar levels. For the $(\alpha+\theta)/\beta$ and θ/β ratios, under LG + HB and HG + HB conditions, the EEG indicators experienced a fall followed by an increase. Unlike the previous indicator, under the condition of HG + LB, the $(\alpha+\theta)/\beta$ and θ/β ratios exhibited an increase and then a decrease. Moreover, at the conclusion of this stage, a noticeable difference was still observed in the levels of EEG among the four conditions.

In the final 2 min of walking, the study entered the sustained phase, during which EEG indicators exhibited a similar trend under different scenrios. However, it is important to consider that the experimental outcomes during this phase may be influenced by the participants' psychological awareness of the experiment coming to an end. During this phase, the β/α ratio experienced a rapid increase, while the other two indicators, $(\alpha+\theta)/\beta$ and θ/β, decreased significantly.

3.3.2. Effect of experience duration under various combinations of greenery and road visibility

Based on Table 4, the ratio of θ/α representing arousal shows a negative correlation with duration. Additionally, all combinations passed either Levene's homogeneity of variance test or Welch's test. Consequently, marginal means were calculated for the cross terms of the mode factors, using this data. Broken line plots were then constructed to analyze the changes in EEG ratio over time.

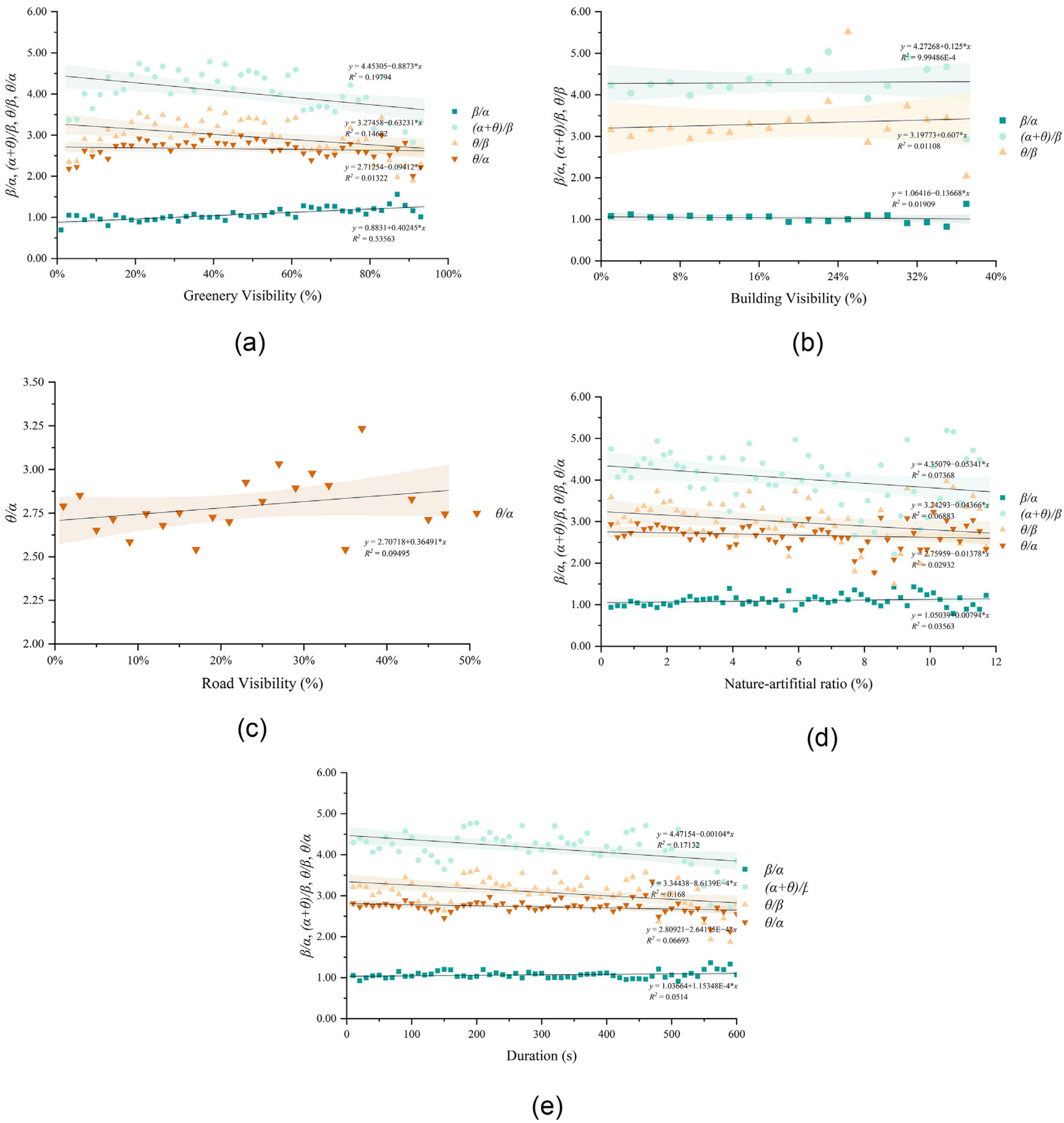


Fig. 5 Relationships between the characteristic values of visual elements and the measured EEG ratios, with linear regressions and correlation coefficients (a) greenery visibility; (b) building visibility; (c) road visibility; (d) nature-artificial ratio; (e) duration.

Figure 11 illustrate the changes in the θ/α ratio over time and across various combinations of greenery and road visibility. Similar to the trend of β/α, $(\alpha+\theta)/\beta$ and θ/β ratios over time, the performance of θ/α ratio can also be divided into three phases: the novelty phase, the adaptation phase, and the sustained phase.

The initial 5 min of the walking process was identified as the novelty phase, during which the level of relaxation exhibited recurrent fluctuations. During this phase, the overall level of the θ/α ratio was generally lower under high greenary scenarios compared to low greenery visibility. This indicated an advantage of high greenery conditions in enhancing relaxation during this period. Additionally, higher level of road visibility under low greenery conditions resulted in lower levels of relaxation, but with higher level of greenery, the difference was relatively vague. Within the novelty phase, the 3rd and 5th minutes served as the extremum, with relaxation levels peaking.

The period from the 6th to the 8th minute was referred to as the adaptation phase, during which the θ/α ratio

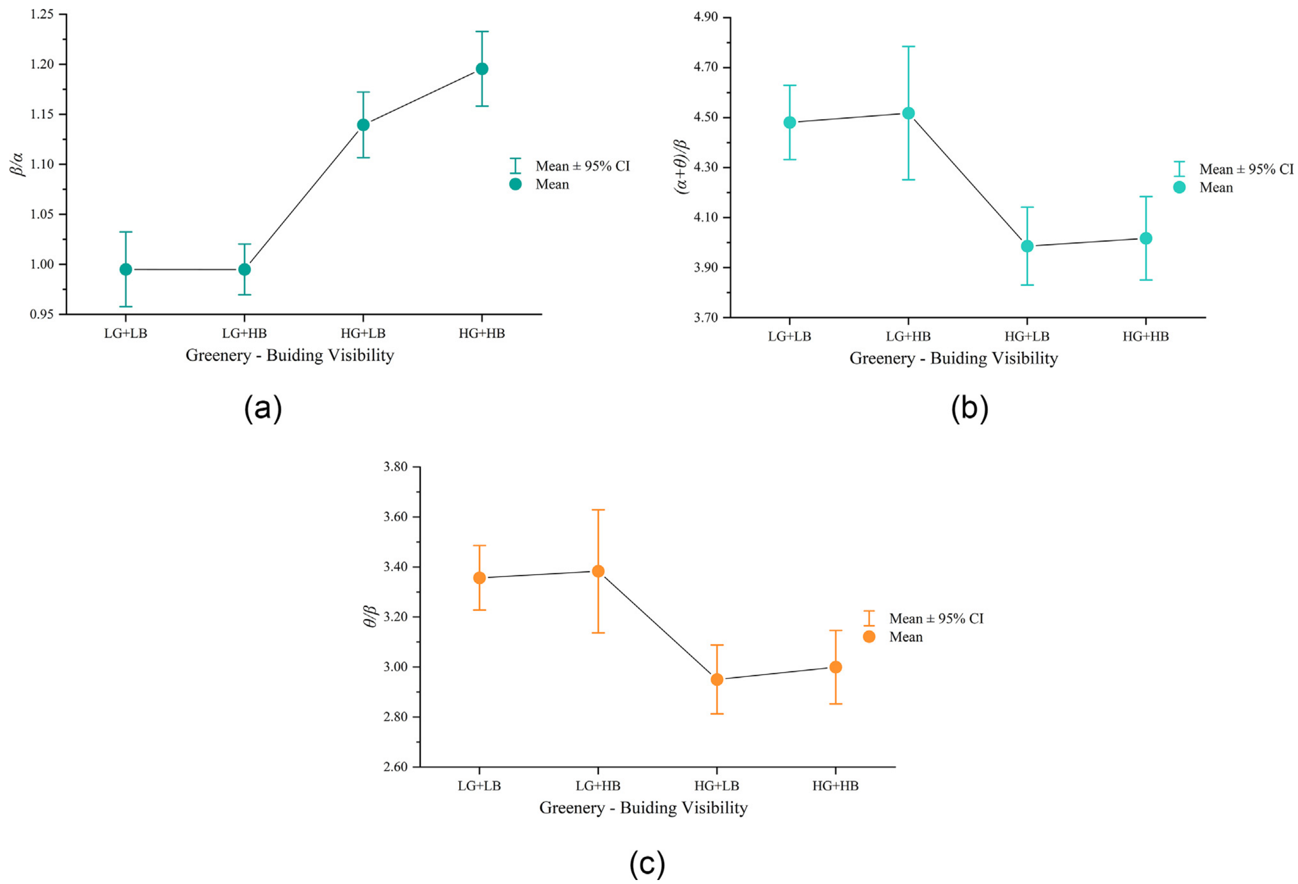


Fig. 6 Mean values of the EEG ratio indicators under the different combinations of greenery and building visibility. (a) β/α. (b) $(\alpha+\theta)/\beta$. (c) θ/β. LG + LB, low greenery, low building; LG + HB, low greenery, high building; HG + LB, high greenery, low building; HG + HB, high greenery, high building.

fluctuated in response to different scenarios. Unlike the novelty phase, no significant and continuous contrast in magnitudes was observed during this period. At this stage, pronounced fluctuations were observed under the HG + LR and LG + LR conditions, while the changes remained relatively stable under the other two scenarios. Under the HG + HR condition, the θ/α ratio experienced an increase followed by a slight decrease, while in the other three conditions, it underwent a fall and rise. By the end of the adaption phase, substantial disparities persisted in the θ/α ratio across different scenarios, with the highest observed under condition of HG + LR and the lowest under LG + HR.

In the final 2 min of walking, the study entered the sustained phase, during which the θ/α ratio exhibited a similar descending trend under different scenrios. However, it is important to consider that the experimental outcomes during this phase may be influenced by the participants' psychological awareness of the experiment coming to an end.

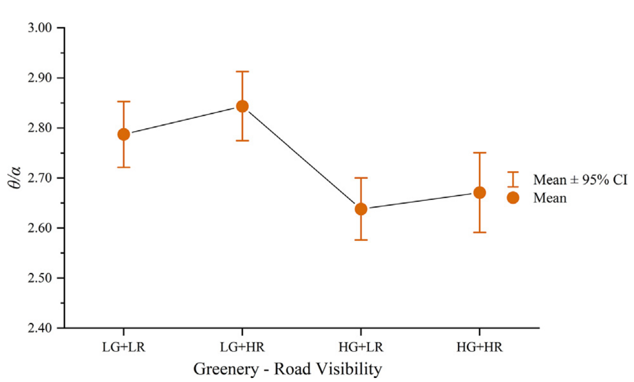


Fig. 7 Comparison between the θ/α ratio and various combinations of greenery and road visibility. LG + LR, low greenery, low road; LG + HR, low greenery, high road; HG + LR, high greenery, low road; HG + HR, high greenery, high road.

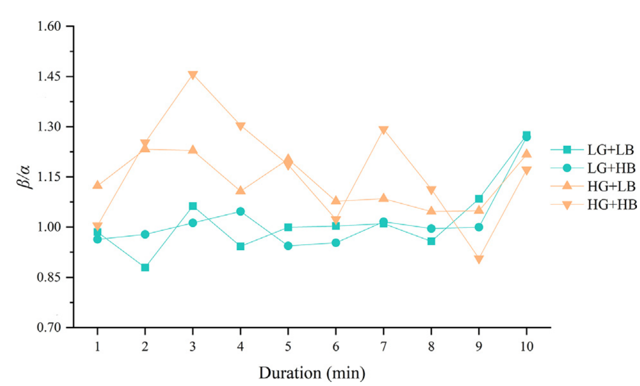


Fig. 8 Changes in the β/α ratio over time and across various combinations of greenery and building visibility.

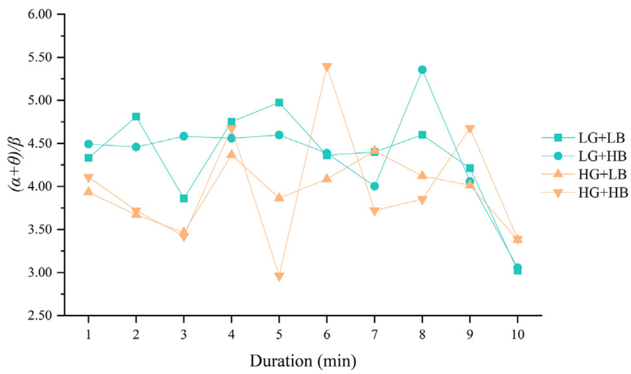


Fig. 9 Changes in the $(\alpha+\theta)/\beta$ ratio over time and across various combinations of greenery and building visibility.

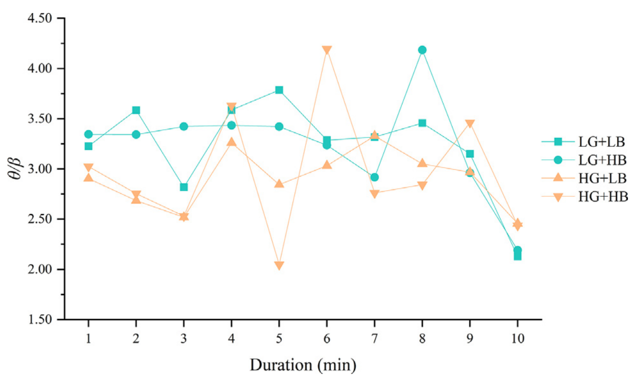


Fig. 10 Changes in the θ/β ratio over time and across various combinations of greenery and building visibility.

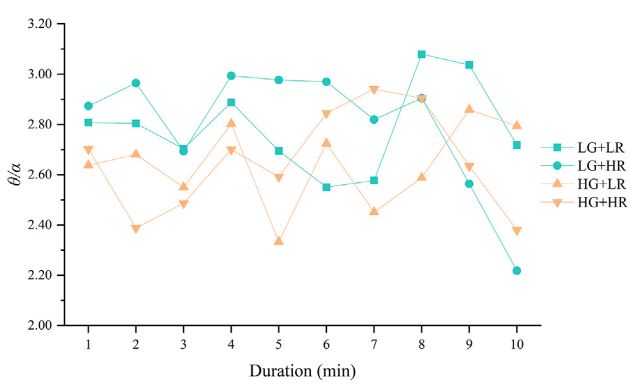


Fig. 11 Changes in the θ/α ratio over time and across various combinations of greenery and road visibility.

4. Discussion

4.1. Effects of landscape sequences components on pedestrians' emotional responses

In previous studies using virtual reality, photos, videos, and static scenes, a preference for natural landscapes over artificial ones has been associated with favorable emotional implications (Al-Barrak et al., 2017; Banaei et al., 2020; Hou et al., 2023; Tilley et al., 2017; Zou et al., 2021). However, it is important to note that the real walking environment differs from these prior studies. In this study, four actual routes were selected, and landscape sequence design elements and brainwave activities were extracted to investigate their influence. The findings of this study suggest that specific elements selectively influence EEG ratio indices. Green visibility consistently displayed an association with all EEG indicators. The θ/α ratio, which represents the level of relaxation, was specifically relevant to road visibility. This may be explained by the diversion of pedestrian focus caused by roads. In contrast, indices such as β/α, $(\alpha+\theta)/\beta$, and θ/β, which denote arousal, fatigue, and attention levels, respectively, manifested associations with building visibility. This could be attributed to the increased visual complexity and cognitive demands presented by buildings in the environment.

The ANOVA analysis conducted in this study aimed to demonstrate the different impacts of visual element combinations on emotional responses. The results revealed the following significant findings. Firstly, a direct correlation was observed between heightened greenery visibility and increased levels of arousal, relaxation, and attention, while fatigue levels decreased. This indicates that prioritizing a greenery visibility threshold of above 51% can have positive emotional implications. The effects of building and road visibility were found to be more complex. In scenarios with low building visibility emerged as ideal, enhancing attention while reducing fatigue. Interestingly, in scenarios with predominant greenery, increasing building visibility further amplified arousal levels. However, it is important to note that the highest building visibility value among the data with high levels of green visibility was 31%. This finding is reminiscent of the work by Kim et al. (2019), who identified contrasting fear responses between architectural and natural nocturnal scenes. Additionally, our findings demonstrated that road visibility ranging from 0 to 10% yielded optimal relaxation levels under conditions of low greenery visibility. In scenarios with higher greenery visibility, relaxation levels approached their peak when road visibility was low. These findings highlight the key role of greenery visibility in emotional regulation, suggesting a design threshold of over 51%. Conversely, the effects of building and road visibility on emotions are more subtle, and require comprehensive consideration alongside greenery coverage rates.

Based on the changes in EEG ratio over time, there are several recommendations for sequence design to enhance and maintain higher levels of arousal, reduce fatigue, and improve attention. Firstly, it is recommended to start with a high level of greenery visibility, with an optimal duration of 5 min. In the middle adaptation phase, designers can select scenes with both high greenery and high building visibility to enhance arousal levels, or choose high greenery and low road visibility to gantuantee optimal levels of fatigue and and sttentionScenes with high greenery visibility and low road visibility is recommended for enhancing relaxation. It is important to consider the large fluctuations in the stimulus cycle when adopting the HG + HB (high greening, high building) model in the adaptation and sustained phases, and ensure that the duration is not too long. In the final period, there is minimal difference between different combinations. While studies have been conducted on the changes in acoustic stimuli elements over time (Li et al., 2019), there is still a lack of consistent real-time feedback research on the temporal dynamics of visual landscapes. Many studies have relied on static images to explore the relationship with physiological indicators (Berto et al., 2010).

Previous research has established that natural landscapes have the potential to restore focus and relieve stress. However, this current study aimed to investigate the real-time emotional changes experienced by pedestrians in response to visual landscapes. It sought to elucidate the influence of different landscape elements on various emotions, and further investigate their interrelationship. The study found that the emotional influence of building and road visibility did not follow a simple inverse relationship across different levels of greenery, suggesting the potential role of routine visual exposures in influencing emotional responses. Moreover, the study highlighted that emotional responses to visual landscapes were not static but rather oscillatory. Different combinations of landscape elements manifested characteristic temporal patterns and peak-valley dynamics.

4.2. Implications for creating pedestrian-friendly landscape environment

In the field of urban design, achieving a balance between natural and artificial landscapes in public spaces is crucial for fostering optimal emotional experiences. Previous research has consistently underscored the favorable emotional responses caused by natural landscapes in comparison to their artificial counterparts. However, the design of urban public spaces should consider the functional demands of settlements, movement, and various activities, by integrating landscapes with human activities. By drawing insights from EEG data, the rational selection of visual landscape elements and proportions can be informed to enhance emotional wellbeing. This investigation depicted that the influence of landscape elements on emotional responses was not universally uniform, thereby emphasizing the importance of precision in design decisions. Notably, the emotional impact of element combinations did not follow a linear trajectory; rather their cumulative effect was contingent upon specific mean levels.

Furthermore, the attainment of a rich visual landscape within urban public spaces necessitates a departure from just one single scene. Instead, a temporally structured sequence of landscapes, guided by emotional feedback from EEG measurements, can significantly booster the emotional experience during walking process. Our findings underscored the temporal dynamics of emotions, demonstrating that successive peaks of positive emotions within the same design mode tended to diminish, while troughs intensified. Moreover, optimal durations for experiential engagement varied across different modes, with distinct EEG levels emerging across specific time spans. By aligning the appropriate visual mode with specific durations, an enhanced emotional experience can be achieved.

5. Conclusion

This study aimed to investigate the correlation between the design and variation of landscape sequences, walking duration, and the real-time physiological feedback and emotions of walkers. To achieve this, we employed a methodology that involved continuous recording the visual images observed by participants as they walked along selected routes within the campus. Additionally, we collected EEG data from the participants. Using a time interval of 5 s, we calculated four types of EEG signal ratios as indicators of emotional feedback. Furthermore, we used an image semantic segmentation tool based on FCN network to extract and calculate specific visibility of visual elements.

Our bullets indicated that θ/α ratio, which reflected the level of relaxation, was strongly correlated with both greenery and road visibility. On the other hand, other EEG ratios, including β/α ratio representing arousal, $(\alpha+\theta)/\beta$ ratio representing fatigue, and θ/β ratio representing attention, were primarily influenced by greenery and building visibility. Additionally, different combinations of visual elements resulted in variations in emotional states. When greenery visibility exceeded 51% and building visibility ranged from 5.2% to 31%, arousal was maximized. The highest level of attention and lowest level of fatigue were observed when greenery visibility surpassed 51% and building visibility was below 5.2%. Participants experienced the highest level of relaxation when greenery visibility exceeded 51% and road visibility was below 10%. Moreover, emotions exhibited temporal variations, with high greenery visibility prominently influencing positive feelings within the initial 5 min. Subsequent periods showed noticeable fluctuations in both high greenery and building visibility, suggesting potential short-term stimuli to augment positive emotions.

The findings of this study highlight the signifcant impact of the arrangement of landscape sequences on the emotional experiences of pedestrians. Therefore, detailed considerations are necessary in terms of element proportions, combinations, and durations to create a design that effectively caters to the emotional needs of the majority. This study provides theoretical support and practical methods for implementing a dynamic landscape environment design that promotes health and well-being.

However, this study has certain limitations that should be considered. Firstly, it only studied the impact of three types of visibility on physiological signals, and overlooking potential interferences during the process of walking, such as sound and light, as well as individual social and behavioral factors. Further research could investigate the combined impact of multiple factors or control variables to minimize the interference of unrelated factors on the results, thereby improving the precision of the analysis and conclusions. Secondly, the four selected route scenes in this study primarily consisted of forest-like natural environments. In order to broaden the applicability of landscape sequence design guidance, it would be beneficial to explore a wider range of scene types.

Declaration of competing interest

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

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