https://doi.org/10.15302/J-LAF-1-020059 RECEIVED DATE | 2021-05-17

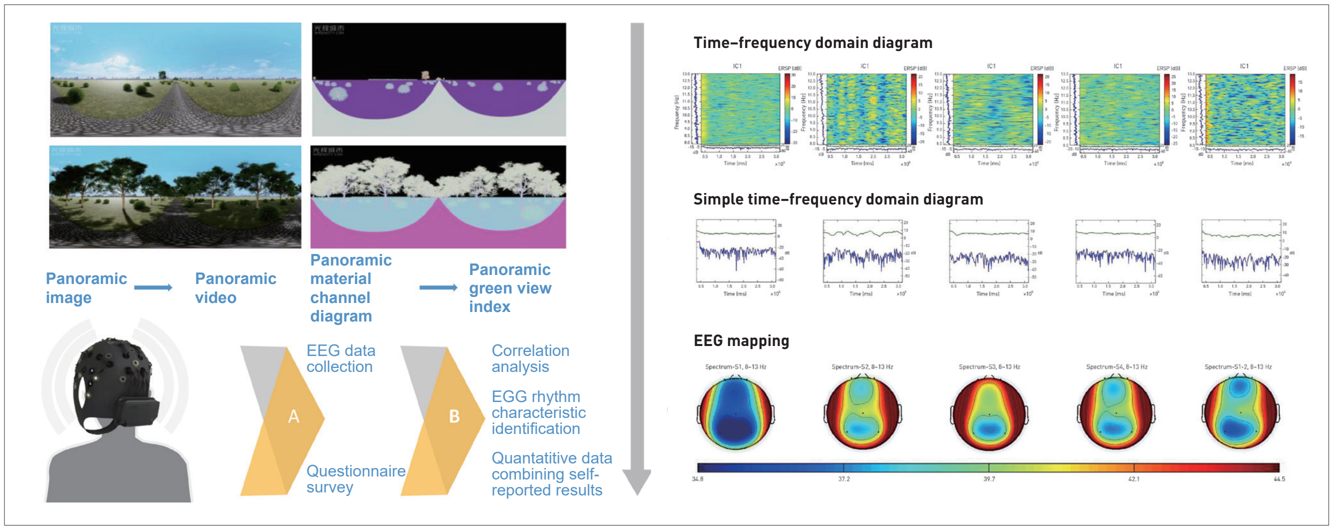
Research on the Impact of Panoramic Green View Index of Virtual Reality Environments on Individuals' Pleasure Level Based on EEG Experiment

NIE Wei[1], JIA Jiangxu[1], WANG Mimi[1], SUN Jin[1], LI Gang[1,2,*]

1 School of Architecture and Urban Planning, Anhui Jianzhu University, Hefei 230022, China
2 Everglades Wetland Research Park, Florida Gulf Coast University, Naples, FL 34112, USA

*CORRESPONDING AUTHOR
Address: No. 292, Ziyun Road, Shushan District, Hefei City, Anhui Province, 230022, China
Email: ligang27@foxmail.com

GRAPHICAL ABSTRACT



HIGHLIGHTS

- Analyzes individuals' pleasure level based on virtual reality and EEG technology
- Pleasure level reaches the highest under the scenario with 60% panoramic GVI
- Extremely high panoramic GVI may lead to negative emotions
- Landscape with carefully designed panoramic GVIs can improve one's pleasure level

ABSTRACT

Green View Index (GVI) is a core indicator to measure urban quality. Identifying proper ranges of GVI has become a significant proposition in Landscape Architecture to design environments that can increase individuals' pleasure level. However, quantitative research on the pleasure level impacted by varied GVIs is still inadequate. This research explores the changes of pleasure level through EEG data collection and questionnaire survey under panoramic scenarios with different panoramic GVIs, which can represent more environmental elements than two-dimensional images. By adding shrubs and trees gradually, this experiment precisely set five scenarios with the GVI changing from 0 to 30%, 60%, 90%, and 0. Research results show that 1) individuals' pleasure level dropped to the lowest when they first enter the scenario with a panoramic GVI of 0, but when panoramic GVI increased from 0 to 30% and to 60%, the pleasure level increased and finally researched the highest; 2) in an environment with a panoramic GVI of 90%, individuals' pleasure level significantly reduced, while some participants self-reported the sense of fear and oppression; and 3) when shifting panoramic GVI from 90% to 0, the bright and open space increased participants' pleasure level. All these findings reveal that individuals' pleasure level reached the highest under the scenario with 60% panoramic GVI; extremely high panoramic GVI may lead to negative emotions; and landscape with carefully designed panoramic GVIs can improve one's pleasure level. Future research may probe into the relationship between GVI and individuals' pleasure level from more perspectives to provide reference for the design, optimization, and evaluation of outdoor urban greening.

KEYWORDS

Panoramic Green View Index;
EEG;
Environmental Psychology;
Landscape Architecture;
Virtual Reality;
Pleasure Level

EDITED BY
WANG Ying, Tina TIAN
TRANSLATED BY
WANG Ying, Tina TIAN, SHEN Ruiqi, YAN Lu

1 Introduction

Priorities for contemporary urban construction in China are given to urban quality improvement and management towards beautiful cities[1]. Meanwhile, the quality of green spaces outweighs the speed of their development, significantly driving improvements of the urban environment[2]. In indicating the effect of greening efforts, green view index (GVI), which evaluates visual greenery from the pedestrian's perspective, is receiving more attention than other commonly-used indicators such as green space ratio[3]. Earlier research in the 1980s showed that an environment with GVI of over 25% was relatively satisfying; when GVI reached 50% or more, users would feel satisfied[4]. Recent research employing GVI analysis of real scenes and satisfaction questionnaire also proves that streetscapes with GVIs of 20% ~ 40% were regarded acceptable by participants, and streetscapes with a GVI of over 40% may please most of the participants[5]. Moreover, the environment with a comparatively high GVI is conducive to emotion regulation, especially to calming down[6][7]; while access to green spaces is also beneficial to both physical and mental health[8], and the quantity of green spaces was positively related to human health[9]. However, the optimal GVI range that can provide reference for urban greening needs further research efforts.

Research methods used in GVI studies are being improved, benefitting from technological advance. Some research employs photographs and models[10]~[13] with cameras that simulate human visual angle. However, the measured GVI and green area using two-dimensional materials may be inaccurate due to bias from perceived differences in visual angles or experiment environments[14]. In recent years, researchers begin to introduce virtual reality (VR) in GVI measurement. For instance, Xu leiqing et al. studied the GVI in VR scenarios of urban streets, and concluded that the higher the GVI was, the more fascinating the streetscape would be[15]. Huang Qiuyun et al. constructed three VR scenarios with varied visible greenery ratios (using cross-view screenshots to calculate the number of pixels associated with vegetation) and measured skin conductance levels, founding that grassy environments had the greatest effect on positive affect[16]. However, most existing GVI research stimulating human visual angle—horizontally 120° and vertically about 50° up and 70° down—may neglect pedestrians' slight body movement such like looking up and down and glancing[17]. Thus, panoramic images covering more environmental elements such as leaves overhead and grass by feet can be used to better simulate humans' actual viewshed[18]. Also, being able to adjust GVIs (and even to simulate extremely high GVIs rarely seen in real environment), VR scenarios created through simulation modeling will solve the problem that regular photographs can hardly fully represent GVI changes of a same site. Other studies prove that no significant difference exists between indoor and outdoor visual evaluation on a same landscape[19], and the visual effects are being reinforced by the advance of VR technology to create virtual natural environments matched the real for people to recover mentally[20]. Now VR technology has been widely used in psychological research due to its efficacy in stimulating different emotions[21]. Combining VR technology, simulation modeling can be utilized to explore the effect of varied panoramic GVIs on individuals' psychological states and emotions.

Pleasure—a comfortable state for humans—is a general indication of positive emotions and related concepts are widely explored, usually by means of questionnaire survey, emotion modeling, etc.[22]~[24] Due to difficulties in sample collection in such research, things like limited sample size and subjective disparity of participants may all impact the validity of outcomes[25]. One solution to this deficiency is utilizing Electroencephalogram (EEG), which detects electrical activity of brain cells, to indicate emotional changes[26]. Emotional changes measured by EEG, comparing to other physiological signals, can hardly be feigned or misled. Therefore, EEG can more accurately indicate individuals' perception of environments[27].

This research evaluates individuals' pleasure level in VR scenarios of varied GVIs by combining EEG experiment and questionnaire survey, hoping to provide reference for the construction and improvement of quality urban greening and living environment.

2 Research Methods

2.1 Participants Recruitment and Experiment Conditions

Due to the complicated and time-consuming preparation, this experiment invited 21 healthy undergraduate and master students (11 males and 10 females who were all right-handed① and with no history of mental illness[28]). All the participants majored in Landscape Architecture, Urban and Rural Planning, and Architecture, and had certain understanding of formal beauty and aesthetics knowledge. The experiment was conducted in the laboratory for environmental behavior studies at Anhui Jianzhu

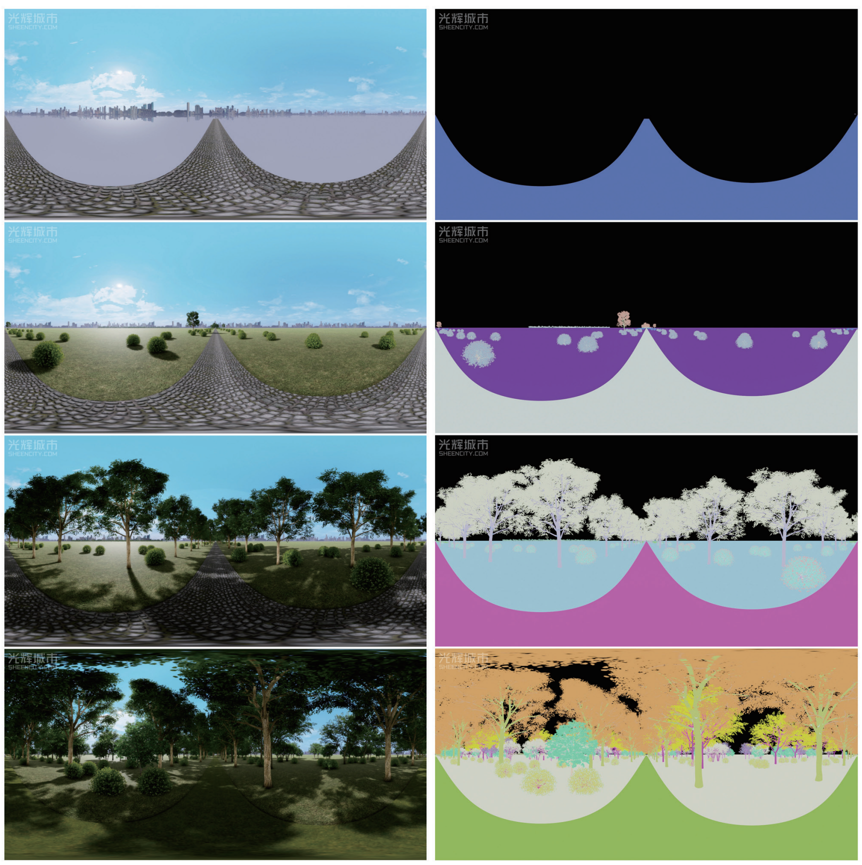
① Right-handed participants are left brain dominant with similar brain structure and state.

University, where the temperature (15°C), humidity (50%), and acoustic (20dB) conditions are constant. Participants were not allowed for taking excitant or pungent foods/drinks such as alcohol 48 hours before the experiment[29]. From November 29 to December 27 of 2020, 21 pieces of raw data were collected, of which 3 pieces were deleted due to electrode disconnection or signal fault. Finally, 18 valid pieces of EEG data were obtained, 10 from males and 8 from females. Both the ex-ante evaluation and ex-post assessment by G*Power software showed that the power was 0.63 under a sample size of 18 and a medium effect size, proving that the experiment results were reliable.

2.2 VR Panoramic Scenario Setting

In this experiment, participants were asked to watch VR scenarios of varied GVIs in an indoor environment, which avoided the disturbance of light, wind, and noise on EEG signal acquisition. Videos used in the VR system presented panoramic images. Via this way, the panoramic GVI can be accurately measured.

1. Panoramic images of scenarios S1 (S1-2), S2, S3, and S4, and their corresponding panoramic material channel diagrams.



1 © Nie Wei

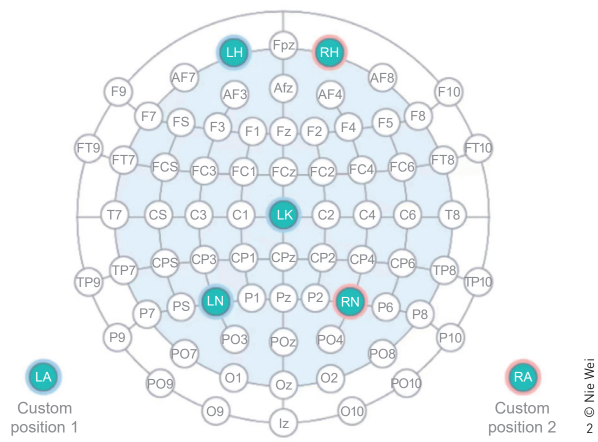
Four panoramic scenario images with different GVIs were created through simulation modeling. The model built in the experiment was rendered with software such as Mars, which can support precise design of environmental elements including roads, buildings, and plants to simulate typical urban green space environments. Ratio of the extracted green pixel amount to the total pixel amount of the panoramic image was used to measure the panoramic GVI. The experiment can adjust the model to control error in GVI setting lower than 1% (Fig. 1). The pre-experiment results indicated that no obvious change of EEG signal existed when GVI slightly changed; a significant fluctuation of EEG signal can be observed when it changed by 30%. Therefore, by adding shrubs and trees gradually, this experiment precisely set four scenarios, namely S1/S1-2 (GVI 0, roads without plants), S2 (GVI 30%, a savanna scenario with roads, lawn, shrubs, and scattered trees), S3 (GVI 60%, an urban green space with trees and shrubs in a medium-level greenery), and S4 (GVI 90%, a large number of trees and shrubs). All of the panoramic images were displayed in a length-width ratio of 2:1, sequentially from S1 to S2, S3, S4, and S1-2.

The video of each panoramic image was played in a VRG Pro headset, with both 3- and 6-minutes versions. Based on pre-experiment results, the 6-minute mode was finally chosen because a longer version would allow participants to better adopt the VR environment so as to lower bias.

2.3 EEG Data Collection

EEG rhythms are brain waves with the same frequency, change period, and recurrence. Brain waves normally range from 1 to 30 Hz and can be divided into Delta, Theta, Alpha, and Beta waves. Particularly, Alpha wave ranges from 8 to 13 Hz, the hallmark frequency of the normal awake and relax brain; while other waves usually occur when individuals' being sleep, overworked, stressed, and excited[30]. It has been proved that positive evaluation is associated with the activation of Alpha waves.[31][32] Many studies in China and other countries have employed relevant EEG rhythms to evaluate individuals' pleasure level and other positive emotions[33]~[36], or measure the comfort level of microclimate factors via changes of the power spectral density of individuals' Alpha waves[37]. Basing on previous findings, this research took Alpha waves as an indicator to measure individuals' pleasure level.

EEG device used in this experiment was wireless EEG electrode caps (EMOTIV EPOC Flex 32 channels) with a sampling frequency of 128 Hz. Altogether, 7 EEG electrodes were placed under the 10–20 International System. The sampling electrodes were Fp1 and Fp2 (frontal lobe), Cz (parietal lobe), P3 and P4 (occipital lobe), and the



2. Electrode position
3. Scene of an EEG experiment employing VR technology
4. Experiment process

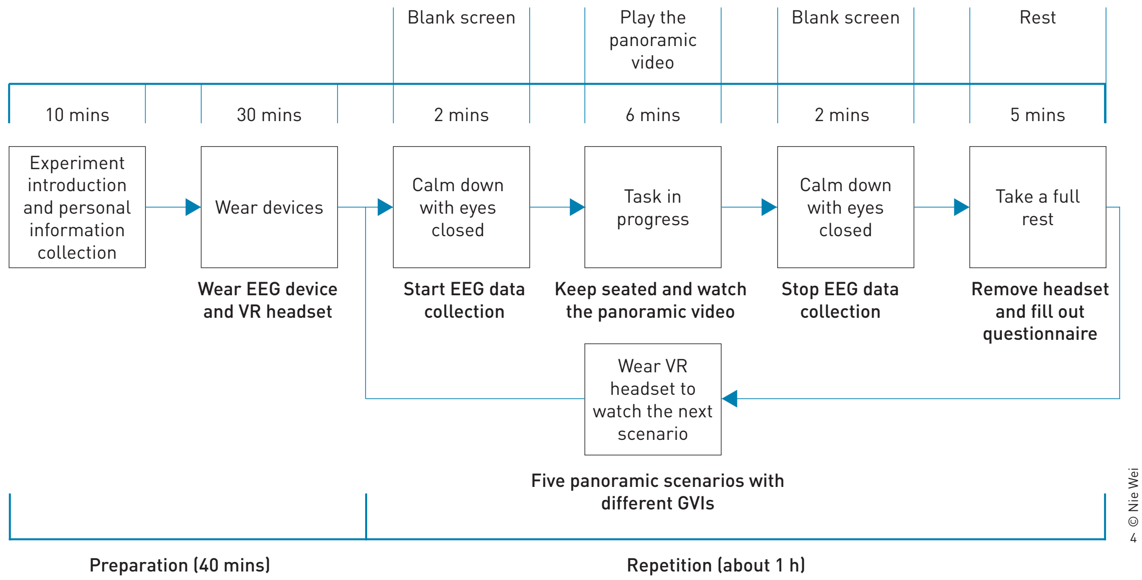


Table 1: Self-reported pleasure level evaluation

Pleasure level	Score	Emotional experience
Not pleasant at all	1	Physical fatigue, agitated; want to remove the VR headset
Not very pleasant	2	Physical and mental fatigue; difficultly finish the experiment
Neutral	3	Not agitated, not comfortable; calmly finish the experiment
Somewhat pleasant	4	Comparatively enjoyable
Very pleasant	5	Very comfortable; eager to stay in the VR scenario

reference electrodes were A1 and A2 (bilateral earlobes) (Fig. 2). After wearing the EEG device and applied EEG cream to reduce the impedance under 1 kΩ, the recording of EEG data started.

After wearing the VR headset, participants were asked to keep their eyes closed for 2 minutes to calm down (Fig. 3); Then they watched VR scenarios S1, S2, S3, S4, and S1-2 in sequence; After this, they removed headsets to rest with eyes closed and filled out questionnaires, which process can reduce the impact of visual fatigue on EEG signals (Fig. 4).

2.4 Questionnaire Survey

The questionnaire survey collected participants' information (gender, age, profession, family background, etc.) and feelings to varied VR scenarios. The latter utilized a Likert Scale (5-point), requiring participants to rate their pleasure level in each GVI scenario (Table 1). The variance analysis result of 0.698 ($p > 0.05$) proves the homogeneity of variance in the questionnaire survey.

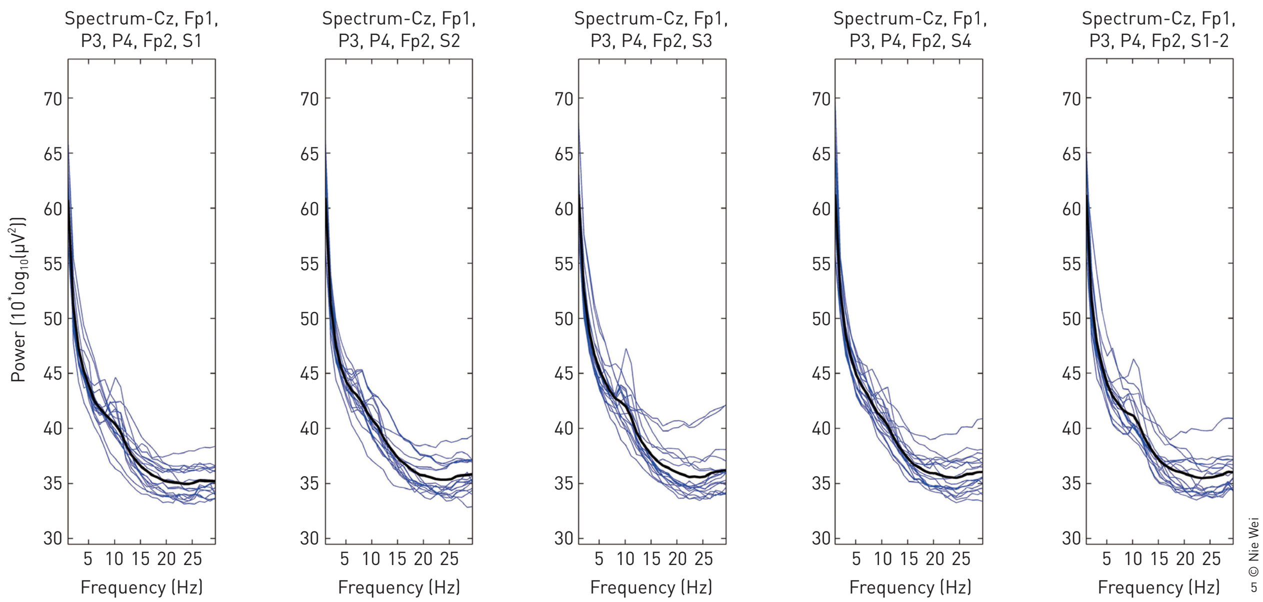
3 Data Processing and Analysis

3.1 EEG Data Processing

This research processed and analyzed 90 pieces of raw EEG data using MATLAB and its plug-in EEGLAB.

1) Pre-processing data by EEGLAB through electrode positioning, high- and low-pass filtering, power frequency filtering, artifact removal by independent component analysis, segment threshold, etc.[38].

2) Inputting the pre-processed data to the study module of EEGLAB, converting the time domain data into frequency domain data by Fast Fourier Transform (FFT) algorithm, and then drawing the average frequency domain maps of EEG rhythms under scenarios S1, S2, S3, S4, and S1-2 (Fig. 5). As the frequency domain analysis can present the distribution of items at different frequencies, power spectrum results obtained by the algorithm can directly represent changes of EEG signals.



5. Average frequency domain diagram of each scenario, where each line represents the frequency domain changes of a participant's *α* waves and the dark thick line in-between represents the average value.

Table 2: Reliability analysis of EEG data

VR scenario	Electrode	CITC value	*α* coefficient after deleting the item	*α* coefficient
S1	Cz	0.485	0.861	
	Fp1	0.461	0.863	
	P3	0.622	0.857	
	P4	0.675	0.855	
	Fp2	0.662	0.858	
S2	Cz	0.435	0.863	
	Fp1	0.517	0.862	
	P3	0.267	0.869	
	P4	0.312	0.868	
	Fp2	0.539	0.861	
S3	Cz	0.604	0.858	
	Fp1	0.248	0.868	
	P3	0.653	0.856	0.868
	P4	0.665	0.855	
	Fp2	0.356	0.865	
S4	Cz	0.335	0.866	
	Fp1	0.358	0.865	
	P3	0.197	0.871	
	P4	0.288	0.867	
	Fp2	0.185	0.869	
S1-2	Cz	0.413	0.864	
	Fp1	0.186	0.870	
	P3	0.486	0.862	
	P4	0.486	0.862	
	Fp2	0.242	0.868	

And 3) EEG α value (i.e. EEG pleasure level, ranging from 0 to 100) was obtained by extracting the data in the unit of dB (digital) from MATLAB by taking the logarithm (base 10) of the power spectral density via the study module. The reliability of the sample size was tested by Cronbach's Alpha coefficient (α coefficient hereafter), and the results (Table 2) showed that the EEG data had a high reliability (0.868)②.

In addition, this research normalized the data with linear function to eliminate the dimensional influence between EEG α value and the questionnaire results by converting the original data into values within the range of [0, 1]. The normalization formula is

$$x_{norm} = \frac{x - x_{min}}{x_{max} - x_{min}} , \quad (1)$$

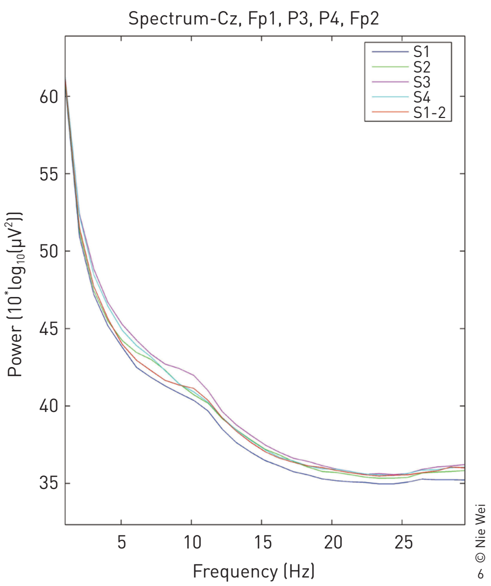
where x_{norm} is the normalized data, x is the original data, x_{max} and x_{min} are the maximum and minimum values of the original data set, respectively.

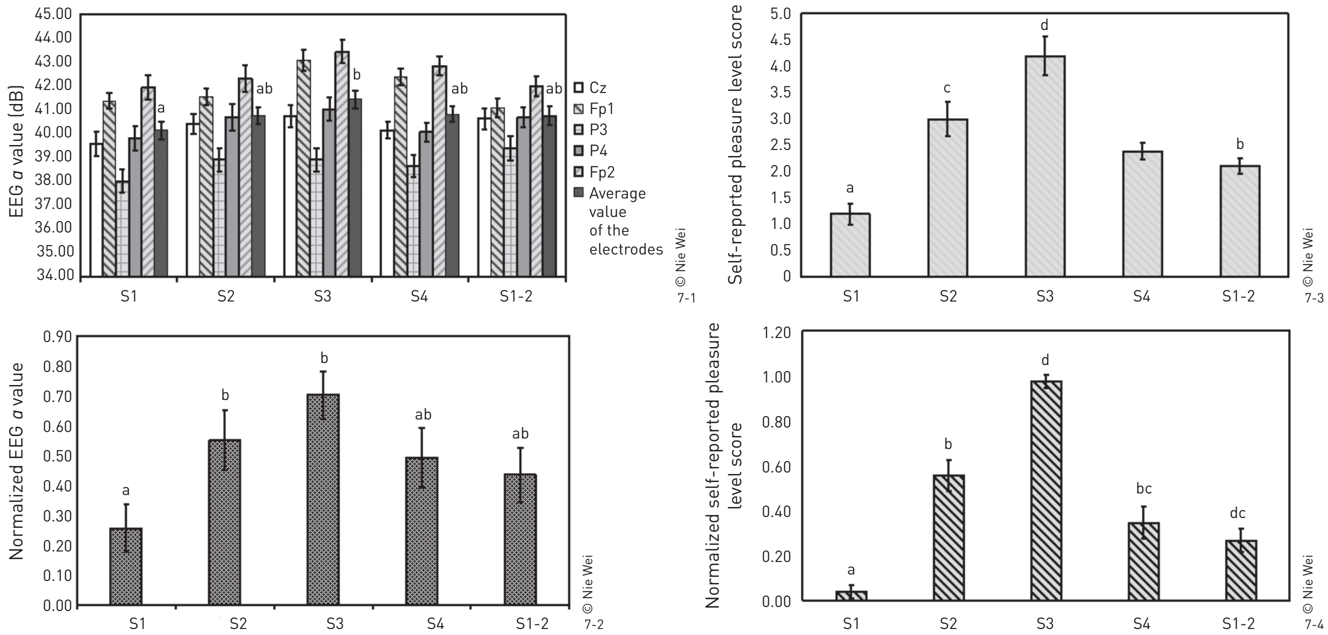
3.2 Analysis of Multiple Groups of EEG Data and Questionnaire Results

This research took the mean value of Alpha wave power for further analysis to eliminate the subtle differences in rhythm between electrodes. The averaged frequency domain map produced by the study module of EEGLAB can clearly show general changes in spectrum frequency (Fig. 6).

Then, this research used SPSS 24.0 to analyze the 90 pieces of EEG data of pleasure level (EEG α value) and 18 pieces of self-reported pleasure level results (Fig. 7). Finally, normalized data of

② In general, *α* coefficient greater than 0.6 is acceptable. When it is greater than 0.8, the data reliability is considered high. If the Corrected Item-Total Correlation (CITC) value is lower than 0.3, the item has a low correlation with other items.





NOTE Letters a, b, c, and d represent the variance between items: items with the same letter are with no obvious difference and items with different letters are with obvious differences.

6. An integrated average frequency domain diagram of all electrodes
7-1. EEG pleasure level results under scenarios S1, S2, S3, S4, and S1-2.
7-2. Normalized EEG pleasure level results under scenarios S1, S2, S3, S4, and S1-2.
7-3. Self-reported pleasure level results under scenarios S1, S2, S3, S4, and S1-2.
7-4. Normalized self-reported pleasure level results under scenarios S1, S2, S3, S4, and S1-2.

Table 3: Independent-samples *t* test for normalized results of EEG pleasure level under varied scenarios

	S1	S2	S3	S4	S1-2
S1	1	2.37*	0.02**	0.83	0.80
S2		1	1.75	0.26	0.40
S3			1	0.55	0.51*
S4				1	0.01
S1-2					1

NOTE * means $p < 0.05$; ** means $p < 0.01$.

Table 4: Independent-samples *t* test for normalized results of self-reported pleasure level under varied scenarios

	S1	S2	S3	S4	S1-2
S1	1	15.52***	0.39***	11.72***	8.96**
S2		1	14.06***	0.07*	1.35**
S3			1	15.13***	12.74***
S4				1	0.95
S1-2					1

NOTE * means $p < 0.05$; ** means $p < 0.01$; *** means $p < 0.001$.

Table 5: Pearson correlation test for normalized results of self-reported and EEG pleasure level under varied scenarios

	Self-reported pleasure level	EEG pleasure level
Self-reported pleasure level	1	0.970**
EEG pleasure level		1

NOTE ** means $p < 0.01$.

EEG and self-reported pleasure level under varied scenarios were tested by independent-samples *t* test and Pearson correlation test. The results are shown in Tables 3 ~ 5.

4 Research Results and Analysis

4.1 EEG Pleasure Level Under Varied Scenarios

Figure 7-2 and Table 3 show that scenarios with normalized EEG pleasure level from high to low are S3, S2, S4, S1-2, and S1, indicating that the EEG α value increases as the panoramic GVI grows until it reaches 90%. Meanwhile, significant difference exists between scenarios S1 and S3 ($p < 0.01$); differences exist between S1 and S2, S3 and S1-2 ($p < 0.05$); but no significant difference is found between other pairs of scenarios.

4.2 Self-reported Pleasure Level Under Varied Scenarios

Figure 7-4 and Table 4 show that scenarios with normalized self-reported pleasure level from high to low are S3, S2, S4, S1-2, and S1. Further, there are very significant differences between S1 and S2, S1 and S3, and S1 and S4 ($p < 0.001$), as well as significant difference between S1 and S1-2 ($p < 0.01$), implying that participants' pleasure level under scenario S1 differed largely from other scenarios.

4.3 Comparative Analysis of EEG and Self-Reported Pleasure Level Under Different Scenarios

Both results of EEG and self-reported pleasure level indicate that participants had the lowest pleasure level under scenario S1 and the highest under scenario S3. Furthermore, as shown in Table 5, the EEG pleasure level has a significant positive correlation with the corresponding self-reported one ($p < 0.01$), i.e. the physiological signs corroborated the self-reported results by participants.

Under scenario S1, the EEG rhythm power of participants dropped the most (Fig. 6); the normalized EEG α value was lower than 0.3 (Fig. 7-2); and the self-reported results implied that participants felt fatigue.

Under scenario S2, participants' EEG pleasure level ($p < 0.05$, Table 3) and self-reported pleasure level ($p < 0.001$, Table 4) were significantly improved. This suggests that environments even with small amount of vegetation may significantly increase users' pleasure level.

Under scenario S3, participants' EEG pleasure level reached the highest (Fig. 7). Results under scenarios S1, S2, and S3 suggest that participants' pleasure level positively correlates with the panoramic GVI. Moreover, participants were emotionally stable when being exposed to scenario S3 with moderate amount of greenery, and feelings such as "relaxed" and "comfortable" were reported. No visual fatigue was reported under this scenario, and their pleasure level increased significantly in a short period of time.

When coming to scenario S4 filled with densely growing vegetation that blocks out sunlight, participants had a strong sense of oppression. As the viewing time increased, some even self-reported the sense of fear, indicating that the panoramic GVI of 90% obviously discomforted participants. Under this scenario, both the EEG and self-reported pleasure levels declined, significantly lower than those under scenarios S2 and S3 (Fig. 7). The quiet laboratory environment (SPL < 20dB) may also make participants more anxious, resulting in uncomfortable feelings such as insecurity[39][40].

4.4 Influence of Scenario Changes on Individuals' Pleasure Level

Participants' self-reported pleasure level under scenario S1-2 was obviously higher than that under scenario S1 ($p < 0.01$, Table 4, Fig. 7-3), though the two scenarios had the same GVI (0). The same variation can be found in the EEG pleasure level results (Fig. 7-2), but the difference was not significant. This might be a result of the scenario change: when under scenario S1, the virtual scene was new to participants; while shifting from scenarios S4 to S1-2, the bright, open space with a lower GVI can help relieve participants' tension and fear.

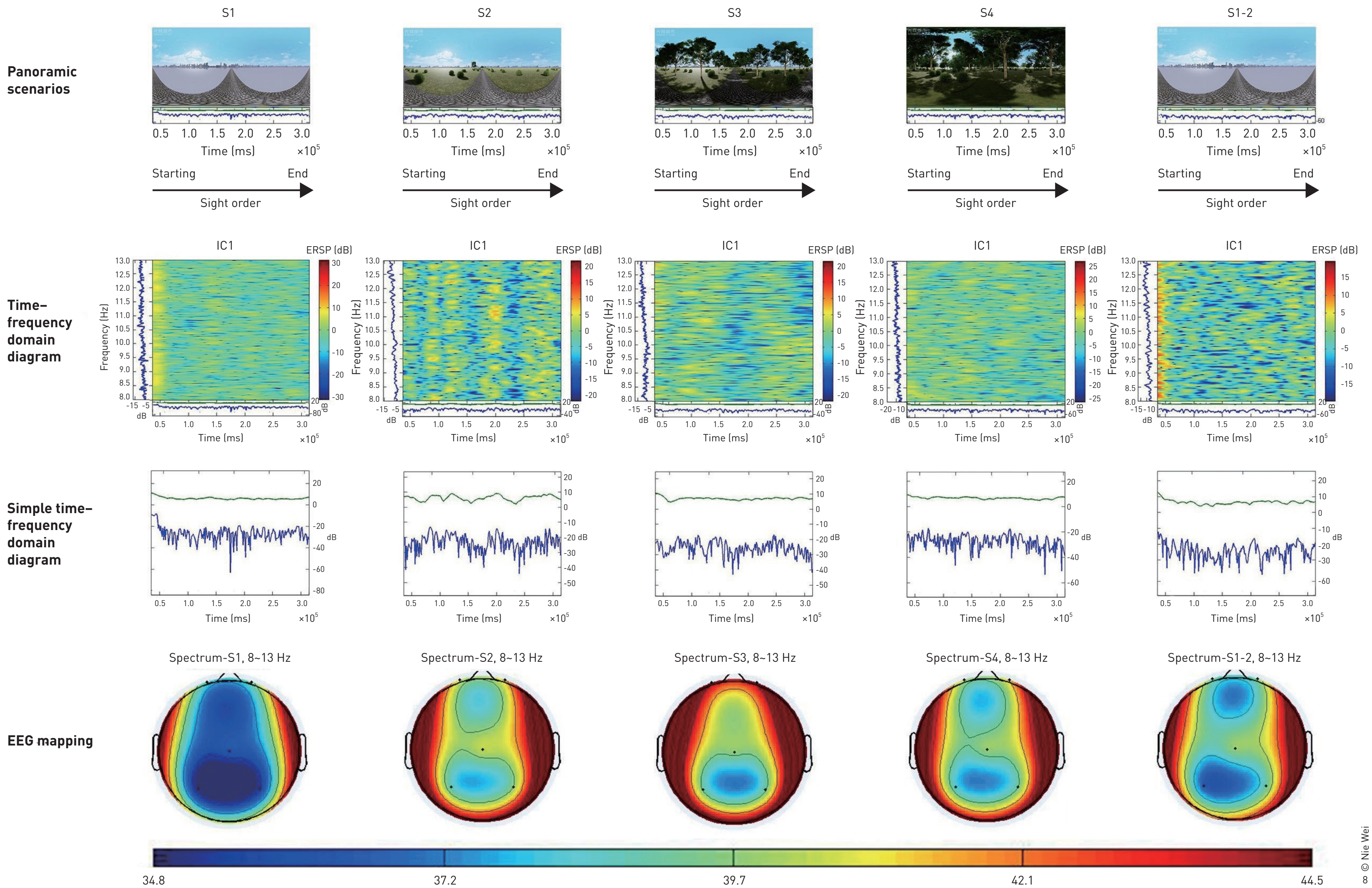
It can be found from above results that extremely high or low panoramic GVIs can neither improve individuals' pleasure level; and shifts of panoramic GVIs, from high to low, may elevate participants' mood. Thus, compared with a landscape site of an unchanged GVI, a landscape with carefully designed multiple panoramic GVIs can effectively improve individuals' pleasure level.

4.5 Time–Frequency Analysis

The time–frequency analysis can clearly show the power spectral density of EEG signals under different scenarios and help identify fluctuations. After deleting the bad data over the first 10 ~ 30 seconds for headset adaptation, the time-domain EEG data were input to EEGLAB. In the generated time–frequency domain diagram, the heat color represents the intensity of EEG α value—the darker the blue (red) color, the lower (higher) the EEG α value (Fig. 8).

The panoramic videos were made by a panoramic image, the both ends of which were connected. Participants remained seated for more precise EEG data collection. The time–frequency domain diagram under scenario S1 indicates that participants had a comparatively high pleasure level due to their being curious and expectant (EEG α value presented in yellow). After this initial stage, the diagram showed a stable pattern, indicating that the EEG α value was little changed under this scenario. From 160 to 200 seconds, the middle period of the experiment when participants exposed to an environment of road pavement, the EEG α value decreased significantly. This implies that VR hard facility would reduce individuals' pleasure level.

After breaks, participants successively experienced scenarios S2, S3, S4, and S1-2. Verified by the time–frequency analysis results, participants who were now familiar with the experimental flow had no obvious mood swing in the first tens of seconds. Under scenario S2 with more vegetation than S1, there were clear segments in the diagram; the EEG α values lowered when participants watched shrubs and hard pavement areas from trees. Participants' overall pleasure level under scenario S3 was higher than under other scenarios—when watching green spaces, the EEG α value increased (in yellow); when watching pavement areas, the EEG α value dropped (in blue). Under scenario S4 with the highest value of panoramic GVI, the diagram pattern is similar to that of S1, where no obvious fluctuation was found. Finally, under scenario S1-2, participants' pleasure level was significantly increased: over the first 30 seconds, the EEG α value was high (in dark red); then the diagram shows a similarity with that of scenarios S1 and S4. These results imply that participants' pleasure level increased quickly when experiencing a shift from the scene with dense trees and shrubs (S4) to a wide, open environment (S1-2).



8. Time–frequency diagram, panoramic images, and EEG mapping under varied scenarios

4.6 EEG Brain Mapping Analysis

EEG brain mapping analysis result (Fig. 8) illustrates that under scenario S1, EEG α values of Fp1, Fp2, Cz, P3, and P4 were low in general (mainly in dark blue). With the increase of panoramic GVI, the brain mapping shows the following characteristics.

1) The diagram turns from dark blue to dark red or yellow, indicating the increase of participants' pleasure level from scenarios S1 to S2 and to S3; From scenarios S3 to S4, the EEG α values decreased significantly.

And 2) when participants experienced different scenarios, EEG α values of frontal lobe (controlling an individual's mental function) and occipital lobe (controlling visual function) changed obviously, while that of parietal lobe (controlling somatosensory function) changed little. This indicates that changes in different brain regions were similar to those under different scenarios, and the frontal and occipital regions were stimulated more obviously.

5 Discussion and Conclusions

This research analyzed individuals' pleasure level changes under VR scenarios with varied panoramic GVIs by integrating both methods of EEG data collection and questionnaire survey, aiming at discovering proper GVI ranges for green space design. Considering that at present panoramic GVI is a new and less-explored indicator in planning and design, this research did not conducted an in-depth theoretical review about it. The results showed that individuals had the lowest pleasure level under the scenario with the GVI of 0. When GVI increased from 0 to 30% and to 60%, the pleasure level increased and researched the highest under the scenario with a GVI of 60%. This is consistent with previous findings by Zheng Lingyu et al.[41] and Ke-Tsung Han[42] that participants' space satisfaction of urban parks reached the highest under GVIs of 30% ~ 60%. Therefore, it is suggested to include the panoramic GVI of 60% into design guidelines for green space that can help enhance users' experience.

Urban green spaces are fundamental for citizens to connect with nature, and quality green spaces and undergrowth can reduce the risk of mental diseases and strengthen people's benefits of physical and mental health[43][44]. Studies based on physiological sensing and VR technology also prove that even in an artificial environment, the site of augmented natural characteristics can bring restorative experience to users[45]. However, few studies explored the threats to health caused by excessive greening. This study found that in an environment with a panoramic GVI of 90%, individuals' EEG and self-reported pleasure levels were both significantly reduced, revealing that an extremely high panoramic GVI may lead to negative emotions. This study also discovers that changed panoramic GVIs in a certain environment can improve individuals' pleasure level. Thus, green space planning and design may employ strategies such as introducing spaces with designed GVIs to enhance users' pleasure level.

Difficulties in this research include complicated, time-consuming sample and data collection, EEG experiment process, and data processing. Regarding the sample size, 18 is valid as proved by previous studies[28][29][36]. This paper displays an experiment that probes into an emerging research interest with integrated methods and available data. Future studies should find a balance between experiment timeliness and complexity, and explore the influence of the disparity of individuals' background (professions, ages, education levels, etc.), so as to better reveal the correlations between panoramic GVIs and individuals' pleasure level.

Furthermore, as the convolutional neural network may identify the areas occupied by tree branches (including voids between leaves) as vegetation segmentations, the panoramic GVI measured in this experiment is about 5% ~ 15% higher than manually-measured results[46]. Thus, it is better to create scenarios with luxuriant foliage when using the convolutional neural network to calculate panoramic GVI, so as to reduce its discrepancy with manual calculation. Taking indoor VR scenarios as the experiment scenes can solve problems existing in current research such as the limitations in real sites, and the low cost-effectiveness of quantitative models. Future research can explore impact of indoor and outdoor environments on VR technology, improve the stimulation precision of VR technology, or combine with the improvement of other environmental factors (e.g. temperature and humidity) or planting design and planting modes for the sites where GVI is low[47][48].

In this research, a combination of traditional research method (questionnaire survey) and EEG data collection improves the scientism of the experiment. With advance in interdisciplinary collaboration and physiological and psychological monitoring technology, future research can construct a VR panorama framework that integrates physiological and psychological knowledge. The research results can provide reference for related sustainable urban design to improve citizens' physical and mental health.

RESEARCH FUNDS

- Study on Slow Travel Optimization Methods for Urban Green Spaces Based on Spatiotemporal Travel Behaviors, Natural Science Foundation of Anhui Province (No. 1908085QE209)
- Study on Layout Optimization for Daily-Recreation-Based and Exercise-Oriented Green Spaces, Key Project of Natural Science Research for Anhui Universities (No. KJ2018A0505)
- 2020 China Scholarship Council Study Abroad Funding Project (CSC No. 202008340054)

REFERENCES

[1] Yu, K. (2020). On the "trio" of beautiful cities. *Landscape Architecture Frontiers*, 8(5), 4-11. doi:10.15302/J-LAF-1-010010

[2] Wang, Z., & Wang, W. (2020). An empirical study on the impact of green spaces in residential areas on the mental health of residents under COVID-19. *Landscape Architecture Frontiers*, 8(6), 46-59. doi:10.15302/J-LAF-0-020009

[3] Liu, B., & Jiang, Y. (2002). The inclined errors and countermeasures of urban green space system planning in China: The research on indices system of the urban green space system planning. *Urban Planning Forum*, (2), 27-29, 79. doi:10.3969/j.issn.1000-3363.2002.02.007

[4] Aoki, Y. (1987). Relationship between perceived greenery and width of visual fields. *Journal of the Japanese Institute of Landscape Architecture*, 51(1), 1-10.

[5] Li, M. (2018). *Visual evaluation of green quantity in walking space of city street based on green visual rate: A case study of Beijing Axis* (Master's thesis). Retrieved from CNKI database.

[6] Li, Z., He, Z., Zhang, Y., Jin, S., Wang, X., Zhu, J., & Liu, S. (2020). Impact of greenspace exposure on residents' mental health: A case study of Nanjing City. *Progress in Geography*, 39(5), 779-791. doi:10.18306/dlkxjz.2020.05.007

[7] Ministry of Land, Infrastructure and Transport. (2005, August 12). *A social experiment survey of the correlation between the amount of greenery in the city and the psychological effect: The green landscape and psychological effects of the city to alleviate the discomfort of midsummer days*.

[8] Nielsen, T. S., & Hansen, K. B. (2007). Do green areas affect health? Results from a Danish survey on the use of green areas and health indicators. *Health and Place*, 13(4), 839-850. doi:10.1016/j.healthplace.2007.02.001

[9] van Dillen, S. M. E., de Vries, S., Groenewegen, P. P., & Spreeuwenberg, P. (2011). Greenspace in urban neighbourhoods and residents' health: Adding quality to

quantity. *Journal of Epidemiology and Community Health*, 66(6), e8. doi:10.1136/jech.2009.104695

[10] Duan, S. (2021). Analyses on the characteristics of greenery amount of roads in residential quarters based on green view index—Taking Rizhao City, Shandong Province as an Example. *Xiandai Horticulture*, 44(5), 20-21. doi:10.14051/j.cnki.xdyy.2021.05.008

[11] Li, Y., & Huang, J. (2020). Evaluation of green view perception of walking environment in historical blocks based on green view attenuation curve: A case study of Tongwen Area, Zhongshan Road of Xiamen. *Landscape Architecture*, 27(11), 110-115. doi:10.14085/j.fjyl.2020.11.0110.06

[12] Pei, Y., Kan, C., & Dang, A. (2020). Street greenspace justice assessment study of Dongcheng District in Beijing based on street view data. *Chinese Landscape Architecture*, 36(11), 51-56. doi:10.19775/j.cla.2020.11.0051

[13] Dong, L. (2021). Research on quality improvement and reconstruction of mixed-function urban villages based on green view index and space syntax. *Sustainable Development*, 11(7), 531-539. doi:10.12677/SD.2021.114065

[14] Wang, T., Yang, X., Hu, S., & Shi, H. (2010). Comparisons of methods measuring green quantity. *Journal of Chinese Urban Forestry*, 8(4), 36-38. doi:10.3969/j.issn.1672-4925.2010.04.011

[15] Xu, L., Meng, R., & Chen, Z. (2017). Fascinating streets: The impact of building facades and green view. *Landscape Architecture*, (10), 27-33. doi:10.14085/j.fjyl.2017.10.0027.07

[16] Huang, Q., Yang, M., Jane, H., Li, S., & Bauer, N. (2020). Trees, grass, or concrete? The effects of different types of environments on stress reduction. *Landscape and Urban Planning*, (193), 103654. doi:10.1016/j.landurbplan.2019.103654

[17] Wang, M., & Peng, H. (2018). A new interpretation on the development of green space in high-density city. *Landscape Architecture Academic Journal*, (1), 28-33. doi:10.3969/j.issn.1000-0283.2018.01.009

[18] Zhu, H., Kong, Y., & Ohno, R. (2021). Visual analysis method of garden tour experience based on panoramic images: A case study of the lingering garden. *Landscape Architecture*, 28(12), 77-84. doi:10.14085/j.fjyl.2021.12.0077.08

[19] Liu, B. (1990). *Systematization of Landscape Engineering* (pp. 23-31). China Architecture and Building Press.

[20] Nukarinen, T., Istance, H., Rantala, J., Mäkelä, J., Korpela, K., Ronkainen, K., Surakka, V., & Raisamo, R. (2020). Physiological and Psychological Restoration in Matched Real and Virtual Natural Environments. In R. Bernhaupt, F. F. Mueller, D. Verweij, J. Andres, J. McGrenere, A. Cockburn, I. Avellino, A. Goguey, P. Bjørn, S. Zhao, B. P. Samson, & R. Kocielnik (Eds.), *CHI EA '20: Extended Abstracts of the 2020 CHI Conference on Human Factors in Computing Systems* (pp. 1-8). ACM. doi:10.1145/3334480.3382956

[21] Chen, Y. (2019). *Research on grading characteristics of EEG signal degree of fear based on VR system* [Unpublished master's thesis, Nanjing University of Posts and Telecommunications]. Retrieved from CNKI Database.

[22] Nie, S. (2017). A study on pleasant degree of campus road landscape: A case study of Huazhong University of Science and Technology. *Interior Architecture of China*, (6), 126.

[23] Gao, X., Dong, H., & Feng, Y. (2020). Research on the Relationship between Street Plant Space and Pleasure of Pedestrian Activity. In *Proceedings of Annual Conference of Chinese Society of Landscape Architecture (Vol. 2)* (pp. 290-298). China Architecture and Building Press. doi:10.26914/c.cnkihy.2020.056851

[24] Han, M., & Zhuang, W. (2017). Evaluation on architectural delight and user satisfaction of architectural space. *South Architecture*, (5), 10-14. doi:10.3969/j.issn.1000-0232.2017.05.010

[25] Aspinall, P., Mavros, P., Coyne, R., & Roe, J. (2013). The urban brain: Analysing outdoor physical activity with mobile EEG. *British Journal of Sports Medicine*, 49(4), 272-276. doi:10.1136/bjsports-2012-091877

[26] Chen, Z., & Liu, S. (2018). Real-time environmental affective experience assessment via wearable sensors. *Chinese Landscape Architecture*, 34(3), 12-17. doi:10.3969/j.issn.1000-6664.2018.03.003

[27] Sun, Y. (2021). *Research on atrium landscape design optimization of commercial complex based on EEG technology* [Master's thesis]. Retrieved from CNKI database. doi:10.27801/d.cnki.gshyy.2021.000243

[28] Lv, Y., Zhang, W., & Shen, D. (2010). Subliminal affective priming effect by faces with different valence: An ERP study. *Acta Psychologica Sinica*, 42(9), 929-938. doi:10.3724/SP.J.1041.2010.00929

[29] Deng, L., Chen, B., Pang, Q., Wen, R., & Xie, B. (2018). Application of EEG technology in emotional design of cultural and creative products. *Journal of Graphics*, 39(2), 327-332. doi:10.11996/JG.j.2095-302X.2018020327

[30] Liu, W. (2019). *Influence of different forest landscape structure space on college students' rehabilitation* [Master's thesis]. Retrieved from CNKI Database.

[31] Liang, J., & Chen, S. (2015). How positive emotion affects cognition: A review on the development of models. *Chinese Journal of Applied Psychology*, 21(2), 157-165. doi:10.3969/j.issn.1006-6020.2015.02.008

[32] Briesemeister, B. B., Tamm, S., Heine, A., & Jacobs, A. M. (2013). Approach the good, withdraw from the bad—A review on frontal Alpha asymmetry measures in applied psychological research. *Psychology*, 4(3A), 261-267. doi:10.4236/psych.2013.43A039

[33] Dou, X. (2021). *research on the influence of aromatic plants on the psychology and physiology of college students based on EEG analysis* [Master's thesis]. Retrieved from CNKI Database. doi:10.27809/d.cnki.gsjgc.2021.000418

[34] Li, Z., & Munemoto, J. (2010). Comparative Study on waterscaped and non-waterscaped spaces using electroencephalogram analysis: Audio-visual experiment on outer spaces of Chinese residential quarters basing on EEG measurement. *Journal of Architecture and Planning (Transactions of AIJ)*, 75(647), 67-74. doi:10.3130/aija.75.67

[35] Shin, Y.-B., Woo, S.-H., Kim, D.-H., Kim, J., Kim, J.-J., & Park, J. Y. (2015). The effect on emotions and brain activity by the direct/indirect lighting in the residential environment. *Neuroscience Letters*, (584), 28-32. doi:10.1016/j.neulet.2014.09.046

[36] Chen, B., Deng, L., Cai, C., Liu, Y., Hong, P., Zhou, Y., & Jiang, H. (2017). Evaluation interactive prototype scheme based on emotional EEG. *Packaging Engineering*, 38(10), 110-114. doi:10.19554/j.cnki.1001-3563.2017.10.025

[37] Jin, M., Zheng, Q., Zheng, C., & Zhao, X. (2018). Study on comfort of micro-climate in urban green space based on EGG. In *Proceedings of 2018 CSES Annual Conference* (p. 3256-3263). Chinese Society for Environmental Sciences, Hefei, China.

[38] Wei, L., Shen, M., Zhang, G., & Shi, Z. (2004). Artifacts removing techniques on EEG waveforms. *Chinese Journal of Applied Psychology*, 10(3), 47-52. doi:10.3969/j.issn.1006-6020.2004.03.010

[39] Jansson, M., Fors, H., Lindgren, T., & Wiström, B. (2013). Perceived personal safety in relation to urban woodland vegetation—A review. *Urban Forestry & Urban Greening*, 12(2), 127-133. doi:10.1016/j.ufug.2013.01.005

[40] Jorgensen, A., Hitchmough, J., & Calvert, T. (2002). Woodland spaces and edges: Their impact on perception of safety and preference. *Landscape and Urban Planning*, 60(3), 135-150. doi:10.1016/S0169-2046(02)00052-X

[41] Zheng, L., Yang, S., Pu, H., Liu, J., Lei, Y., & Wang, D. (2020). Visible green index research based on space satisfaction of urban park. *Journal of Chinese Urban Forestry*, 18(2), 30-34. doi:0.12169/zgcsly.2019.08.18.0001

[42] Han, K.-T. (2017). The effect of nature and physical activity on emotions and attention while engaging in green exercise. *Urban Forestry & Urban Greening*, (24), 5-13. doi:10.1016/j.ufug.2017.03.012

[43] Tost, H., Champagne, F. A., & Meyer-Lindenberg, A. (2015). Environmental influence in the brain, human welfare and mental health. *Nature Neuroscience*, 18(10), 1421-1431. doi:10.1038/nn.4108

[44] Li, T., Xue, B., Yang, X., Zhang, L., & Wang, Z. (2020). Research on attention recovery in restorative environment based on wireless physiological sensor and virtual reality technology. *Chinese Landscape Architecture*, 36(12), 62-67. doi:10.19775/j.cla.2020.12.0062

[45] Zhang, J., Gong, M., Wu, J., Nan, H., & Dong, L. (2020). Effect of different forest environments on people's physical and mental health. *Chinese Landscape Architecture*, 36(2), 118-123. doi:10.19775/j.cla.2020.02.0118

[46] Zhang, W., Zhou, Y., & Yang, M. (2019). Research on automatic identification and measurement of panoramic visible green index. *Landscape Architecture*, 26(10), 89-94. doi:10.14085/j.fjyl.2019.10.0089.06

[47] Wang, Y., & Huang, J. (2021). Construction of evaluation model of urban ecological comfort index based on green view index. *Acta Ecologica Sinica*, 41(6), 2170-2179. doi:10.5846/stxb202005121189

[48] Zhao, L., Bian, Y., Rong, J., Liu, X., & Shu, S. (2015). Evaluation method for pedestrian level of service on sidewalks based on fuzzy neural network model. *Journal of Intelligent & Fuzzy Systems*, 30(5), 2905-2913. doi:10.3233/IFS-151753

https://doi.org/10.15302/J-LAF-1-020059　中图分类号 | TU985　文献标识码 | A　　收稿时间 | 2021-05-17

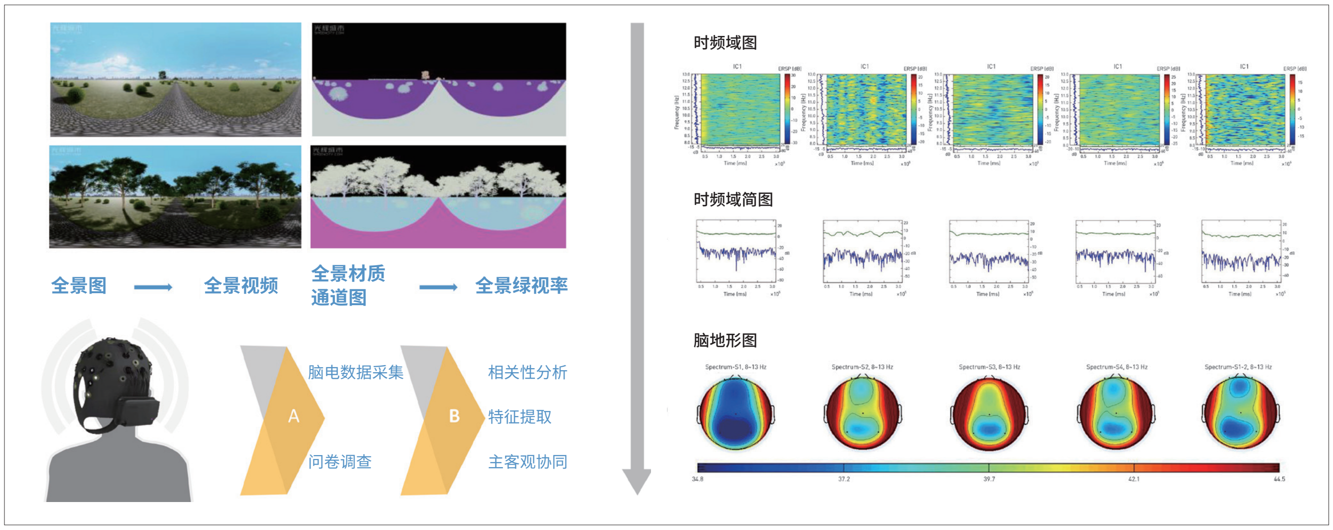
基于脑电实验的虚拟现实环境全景绿视率对人体愉悦度的影响研究

聂玮[1]，贾江旭[1]，王敉敉[1]，孙进[1]，李罡[1,2,*]

1 安徽建筑大学建筑与规划学院，合肥 230022
2 美国佛罗里达海湾海岸大学大沼泽地研究中心，那不勒斯 34112

***通讯作者**
地址：安徽省合肥市蜀山区紫云路292号
邮编：230022
邮箱：ligang27@foxmail.com

图文摘要



文章亮点

- 基于虚拟现实技术和脑电技术分析人体愉悦度
- 当全景绿视率为60%，人体愉悦度可能最佳
- 过高的全景绿视率可能使观者产生负面情绪
- 有规律地提高全景绿视率能够提高个体愉悦度

摘要

绿视率是衡量城市品质的重要参考指标。如何通过适宜的绿视率营造良好人居环境，提高人体愉悦度是风景园林学的重要研究内容。当前绿视率对人体愉悦度的影响仍缺少定量研究。基于全景图测量的全景绿视率可涵盖超出普通二维图像的环境要素，因此本文通过调查问卷和脑电信号（EEG）数据，探究不同全景绿视率环境下个体愉悦度变化规律。实验通过依次添加灌木、乔木等植被，精准控制预景中的全景绿视率，使其按照0、30%、60%、90%、0的顺序变化。研究结果表明：1）个体愉悦度在初次观看全景绿视率为0的环境时最低，并随全景绿视率增加而提升，全景绿视率为60%时被试愉悦度最高；2）全景绿视率为90%时，被试愉悦度显著下降，部分被试出现恐惧、压抑的情绪特征；3）全景绿视率由90%重新回到0时，被试愉悦度明显提高，主观体感从枯燥、无聊转为开敞、明亮。上述结果表明，当全景绿视率为60%，人体愉悦度可能最佳；过高的全景绿视率可能给人带来压力，并显著降低愉悦度；交替变化的绿视环境可能比单一的环境更能提高游憩愉悦度；绿视率与个体愉悦度之间的复杂性有待深入研究。本研究成果可为户外绿化环境的设计、优化及评估提供科学依据。

关键词

全景绿视率；
脑电信号；
环境心理学；
景观设计；
虚拟现实；
愉悦度

编辑 王颖，田乐
翻译 王颖，田乐，申瑞琪，闫露

1 引言

提升城市品质、建设与管理高品质“美丽城市”是当代中国城市建设的要务之一[1]。目前，绿地建设正从高速发展向高质量发展转变，绿地品质的提升是城市环境改善的基础[2]。由于绿地率等城市绿化指标难以确切反映相应空间中的绿化品质与效果[3]，反映人的视野里绿色植被所占比率的绿视率日益受到关注。20世纪80年代的早期研究认为，绿视率大于25%时个体体验较好，当绿视率达到50%以上时个体对所见环境感到满意[4]。近年基于实景绿视率分析与满意度问卷调查的研究表明，当街道景观绿视率为20%~40%时，游览者认为环境良好，当绿视率高于40%时，大部分人表示满意[5]；绿视率相对较高的环境有助于平复市民情绪，使之获得清凉、宁静等积极情绪[6][7]；接触绿地环境有益身心健康[8]，在一定程度上绿地面积与人体健康程度呈正相关关系[9]。但当前城市绿化中绿视率的最佳范围尚不明确，有待进一步研究。

随着技术手段的不断革新，绿视率的研究模式也在不断优化。部分研究通过照片、模型等载体[10]~[13]，利用相机镜头模拟人的视角，来测算一定区域的绿视率。但基于二维图像测算的绿视率和绿量因视角与环境的不同而变化[14]。随着虚拟现实（VR）技术开始应用于绿视率研究中，徐磊青等研究了三维虚拟街道场景下的绿视率，认为绿视率与街道迷人性在一定条件下成正比[15]。黄秋韵等构建了三种具有不同绿视率的VR场景，并取其二维图像的交叉视图测算可视植被像素比例，结合问卷调查及皮电传导水平（SCL）测量，发现草木占比高的环境能更好地缓解人的压力[16]。上述关于绿视率的研究多采用行人视角取景，即取景的水平视角约120°，垂直视角分别约为上50°、下70°。这种取景方法可能忽略行人行进过程中的抬低头及瞥视行为，从而造成取景不全[17]。以全景图像为视觉载体可以辐射人眼视点周边的全部空间，最大程度还原被试在自然环境下的视觉状态，不会因视角固定而忽略头顶枝条、脚下花草等绿视元素[18]，可更好地反映绿地环境的质量。实景环境照片通常难以精准反映同一处场地的绿视率变化，而仿真建模不仅可实现同一环境下绿视率的定量增减，还可模拟实景环境中相对少有的超高绿视率环境。已有研究表明，室内与室外基于同一景观的视觉评价差异不显著[19]。随着VR技术的发展，个体身处虚拟绿地环境同样能获得益处，甚至可能更利于恢复积极情绪[20]。如今VR技术在心理研究领域应用比较广泛，尤其是在情绪的诱发方面[21]。因此，可借助VR技术仿真建模，研究全景绿视率及其变化对个体心理和情绪的影响。

愉悦是一种综合性积极情绪，是理想的舒适状态。与愉悦有关的概念被广泛运用于研究中，以评估个体主观上所体验到的快乐，研究者常采用问卷调查、构建情绪模型等方法评价个体愉悦度变化[22]~[24]。此类研究的样本采集存在一定困难，因而样本量有限、个体主观差异等因素可能影响研究结果的科学性[25]。作为脑神经细胞的电生理活动，脑电信号（Electroencephalogram，EEG）是大脑神经细胞的周期性放电结果，因而可利用EEG量化记录分析人的情绪变化[26]。相对其他生理信号，脑电信号反映出的情感变化难以被伪装或误导，可作为评价人对环境感知的客观定量指标[27]。

本文将脑电信号及全景绿视率作为定量指标，结合问卷调查的定性指标，虚拟现实环境全景绿视率对人体愉悦度的影响，旨在为城市绿化品质及人居环境改善提供参考依据。

2 研究方法

2.1 实验人员及条件设置

因实验准备繁琐、持续时间较长，实验共邀请到21位健康的大学本科生及硕士研究生作为被试（男性11位、女性10位，均为右利手①且无精神疾病史[28]）。被试均来自设计应用类专业（风景园林学、城乡规划学和建筑学），以确保其具备一定的形式美法则和审美素养基础。实验地点为安徽建筑大学环境行为研究专业实验室，可确保被试个体处在恒定的温度（15℃）、湿度（50%）及声环境（20dB）下。脑电数据采集前48小时内，被试禁止摄入酒精等可能具有刺激作用的食物[29]。实验时间为2020年11月29日至2020年12月27日。共获得21份原始数据，其中3份原始数据因电极连结松脱或信号故障等原因剔除。最终获得有效脑电数据18份，其中男性被试数据10份，女性被试数据8份。G*Power软件的事前和事后分析显示，当本研究有效被试人数为18、效应量为中等时，统计功效为0.63，表明实验结果可信。

2.2 VR全景环境获取

实验采用VR技术为被试提供不同绿视率环境的观看体验。室内环境下的VR场景可规避真实场景中光、风、噪音等因素对脑电信号采集的干扰。适用于VR系统的全景图以全景视频的形式展现，可准确测算全景绿视率。

实验采用仿真建模技术，构建了四种不同绿视率的虚拟全景预景。首先利用Mars等软件构建并渲染模型，其次采用软件自带程序精确控制道路、建筑、植物等元素，构建出典型的城市绿地环境。由提取的绿色色块像素量与全景图总像素量之比得出全景绿视率；该模型可将绿视率误差控制在1%以内（图1）。预实验发现，当全景绿视率变化幅度较小时，脑电信号变化不明显。当变化幅度设置为30%时，可有效提升并监测到脑电信号波动幅值。因此，实验通过依次添加灌木、乔木等植被，精准控制预景中的全景绿视率，使其按照0、30%、60%、90%、0的顺

① 均为右利手表明被试为左脑占主导的人群，拥有相近的大脑环境与状态。

序变化。为方便区分，预景依次命名为S1、S2、S3、S4、S1-2——S1和S1-2为无绿植环境（仅道路），S2为道路、草坪与灌木及零星乔木环境（模拟稀树草原），S3为乔灌木数量中等的环境（模拟城市林地），S4为大量乔灌木环境。所有预景中的绿地均以2：1全景图形式展现。

处理完成的全景图以全景视频的形式在VRG Pro头盔中播放，每个预景设有3分钟和6分钟两种播放时长。预实验结果表明，3分钟档位实验时间过短，可能因被试难以充分融入虚拟环境而造成研究结果偏差较大，故将正式实验中单个预景的播放时长定为6分钟。

2.3 脑电数据指标监测

脑电节律是频率范围、变化周期相同、重复出现的脑电波。一般情况下，脑电波集中在1~30Hz，并可根据频率高低分为四个波段：δ波、θ波、α波和β波。其中α波频率为8~13Hz，通常在大脑清醒且放松的状态下出现，而其他波段则常在睡眠、疲惫、紧张亢奋时出现[30]。已有研究表明，积极评价与大脑α波激活相关。[31][32]国内外已有较多研究利用相关脑电节律来评价愉悦等积极情绪[33]-[36]，另有研究利用个体α波的功率谱密度变化研究微气候因子舒适性[37]。参考上述既有研究，本研究采用脑电节律α波作为客观脑电愉悦度指标。

本实验脑电仪采用无线EEG电极帽（EMOTIV EPOC Flex 32通道），采样频率为128Hz。脑电电极定位采用国际标准10-20系统，电极数为7个。其中，采样电极为Fp1和Fp2（额叶）、Cz（顶叶）、P3和P4（枕叶），参考电极为A1和A2（双侧耳垂）（图2）。佩戴脑电仪后，涂抹脑电膏将阻抗降低至1kΩ以下时开始记录脑电数据。

实验开始前，被试佩戴VR头盔，之后需闭目2分钟平静情绪（图3）。再依次观看S1、S2、S3、S4、S1-2预景视频。之后闭目休息、摘取头盔、填写调查问卷，以减少连续观看时视觉疲劳对脑电数据的影响（图4）。

表 1：主观愉悦情绪强度判定

愉悦度	评分	被试体验
非常不愉悦	1	生理疲惫、心理麻痹，希望能取下 VR 头盔
较不愉悦	2	身心疲惫，但能坚持完成实验
无不愉悦	3	无烦躁知觉，无舒适体验，能正常完成实验
较为愉悦	4	实验体验较好
非常愉悦	5	身心非常舒适，愿意长时间处于 VR 环境中

2.4 问卷调查

主观评价主要通过问卷形式，收集被试的基本信息（性别、年龄、专业、家庭背景等）及其对虚拟环境的愉悦度评价。后者采用李克特量表评分法（1~5分），要求被试对在每个全景绿视率预景中的愉悦度进行评价（表1）。方差分析结果显示显著性为0.698（$p>0.05$），表明方差齐性。

3 数据处理与分析

3.1 脑电数据处理

研究利用MATLAB软件及其插件EEGLAB对90份原始脑电数据进行分析处理:

1）通过EEGLAB按顺序进行电极定位、高低通滤波、工频滤波、ICA后手动去伪迹、分段卡阀值等步骤，完成脑电数据预处理[38]。

2）将预处理后的数据导入EEGLAB的study模块，通过快速傅里叶变换（FFT）算法将时域数据转化为频域数据，并绘制S1、S2、S3、S4和S1-2预景下脑电节律平均频域图（图5）。频域分析能够呈现事物在不同频率上的分布情况，利用其算法得出的功率谱参数可直观表现脑电信号的变化。

3）利用study模块将功率谱密度值对10求取对数得出单位为db的数据，在MATLAB中以数字形式提取该数据并将之定义为脑电α值（即脑电愉悦度值），取值范围为0~100。为检验样本量为18的数据是否可信，对原始脑电数据进行信度分析。使用克隆巴赫系数（简称α系数）测量。从表2可知，α系数值为0.868，表明脑电数据信度较高②。

为了消除脑电α值指标与主观评价指标之间的量纲影响，研究需要进行数据归一化处理。本文采用线性函数归一化脑电数据和主观评价数据，将原始数据转换为[0，1]范围内的数值。归一化公式为：

$$x_{norm}=\frac{x-x_{min}}{x_{max}-x_{min}} \quad (1)$$

其中，x_{norm}为归一化后的数据，x为原始数据，x_{max}、x_{min}分别为原始数据集的最大值和最小值。

3.2 多组脑电与主观数据分析

因采集电极分属不同脑域，不同电极之间采集的脑电节律存在微小差异。为消除上述差异，实验取电极数据平均值作为α波能量数值。通

② 一般认为，α 系数大于 0.6 即可，当 α 系数大于 0.8 时，代表数据信度高。如果校正的项总计相关性（CITC）值低于 0.3，则代表该项与其他项关联度较低。

表 2：脑电数据信度分析

虚拟现实环境	电极	CITC 值	项已删除的 α 系数	α 系数
S1	Cz	0.485	0.861	0.868
	Fp1	0.461	0.863	
	P3	0.622	0.857	
	P4	0.675	0.855	
	Fp2	0.662	0.858	
S2	Cz	0.435	0.863	
	Fp1	0.517	0.862	
	P3	0.267	0.869	
	P4	0.312	0.868	
	Fp2	0.539	0.861	
S3	Cz	0.604	0.858	
	Fp1	0.248	0.868	
	P3	0.653	0.856	
	P4	0.665	0.855	
	Fp2	0.356	0.865	
S4	Cz	0.335	0.866	
	Fp1	0.358	0.865	
	P3	0.197	0.871	
	P4	0.288	0.867	
	Fp2	0.185	0.869	
S1-2	Cz	0.413	0.864	
	Fp1	0.186	0.870	
	P3	0.486	0.862	
	P4	0.486	0.862	
	Fp2	0.242	0.868	

表 3：不同预景下脑电愉悦度归一化结果独立样本 *t* 检验

	S1	S2	S3	S4	S1-2
S1	1	2.37*	0.02**	0.83	0.80
S2		1	1.75	0.26	0.40
S3			1	0.55	0.51*
S4				1	0.01
S1-2					1

注 * 代表 $p<0.05$；** 代表 $p<0.01$。

表 4：不同预景下主观愉悦度归一化结果独立样本 *t* 检验

	S1	S2	S3	S4	S1-2
S1	1	15.52***	0.39***	11.72***	8.96**
S2		1	14.06***	0.07*	1.35**
S3			1	15.13***	12.74***
S4				1	0.95
S1-2					1

注 * 代表 $p<0.05$；** 代表 $p<0.01$；*** 代表 $p<0.001$。

表 5：不同预景下主观愉悦度和脑电愉悦度归一化结果皮尔逊相关性检验

	主观愉悦度	脑电愉悦度
主观愉悦度	1	0.970**
脑电愉悦度		1

注 ** 代表 $p<0.01$。

过EEGLAB的study模块绘制的综合电极平均频域图可清晰呈现综合频率的变化（图6）。

采用SPSS 24.0分析90组脑电节律愉悦度数据（α 值）和18组主观愉悦度（主观评价）数据，统计结果如图7所示。最后对不同预景下脑电节律和主观愉悦度的归一化结果进行独立*t*检验与皮尔逊相关性检验，结果如表3~5所示。

4 结果与分析

4.1 不同全景绿视率预景下的脑电愉悦度

由图7-2和表3可知，脑电愉悦度（归一化数值）由高到低的预景依次为S3、S2、S4、S1-2和S1，这表明全景绿视率的逐渐提高带动了被试脑电 α 值的有效提升，但过高的全景绿视率导致了脑电 α 值的下降。同时，S1与S3之间存在显著差异（$p<0.01$）；S1与S2、S3与S1-2之间存在差异（$p<0.05$）；其他预景之间并未发现显著差异。

4.2 不同全景绿视率预景下的主观愉悦度

由图7-4和表4可知，主观愉悦度由高到低的预景依次为S3、S2、S4、S1-2、S1。S1与S2、S3、S4存在极显著差异（$p<0.001$），与S1-2存在显著差异（$p<0.01$）。这表明被试在S1预景下与其他预景下的观感体验差异明显。

4.3 不同全景绿视率预景下脑电和主观愉悦度的比较分析

本研究中的脑电愉悦度和主观愉悦度实验结果均表明，被试的愉悦

度在S1预景中最低，在S3预景中最高。如表5所示，脑电愉悦度与主观愉悦度显著正相关（$p<0.01$），表明生理指标与被试的主观评价结果一致。

在S1预景下，被试的脑电节律能量值最低（图6）；脑电α值归一化结果低于0.3（图7–2）；同时主观评价结果显示，被试表现出疲惫等情绪。

在S2预景下，被试的主观愉悦度（$p<0.001$，表4）与脑电愉悦度（$p<0.05$，表3）显著提升。这表明即使是绿色植被量较少的环境也可能明显增加观者的愉悦感。

S3预景下被试脑电愉悦度最高（图7）。S1、S2及S3的相关结果表明，愉悦度与绿视率变化呈正相关。被试在绿色植被绿量适宜的S3预景下情绪稳定，郁郁葱葱的自然环境带来了放松与舒适感，被试在植被环绕的环境中几乎未出现视觉疲劳，短时间内个体愉悦度水平明显提升。

在植被量大、密不透光的S4预景中，被试表达受到了明显的压抑感；随着观看时间的增加，被试压抑感增加，个别被试甚至自报告出现恐惧感，表明90%的全景绿视率带来明显的不适情绪。最终反映为脑电与主观愉悦度的下降，且显著低于S2和S3预景（图7）。实验室静谧的环境也可能增加人体的紧张情绪（SPL<20dB），进而导致不安全感等不适情绪的出现[39][40]。

4.4 环境交替变化对人体愉悦度的影响

S1–2与S1预景的绿视率均为0，但前者主观愉悦度显著高于后者（$p<0.01$，表4，图7–3）。脑电愉悦度两者差异虽不显著，但前者仍高于后者（图7–2），趋势与主观愉悦度一致。这可能与全景绿视率变化顺序有关：在S1预景中，被试尚未体验模拟场景及变化。在S1–2预景实验过程中，当从S4的高全景绿视率转为开敞、明亮的低全景绿视率时，可能有助于缓解紧张、恐惧情绪。

上述结果表明，过高与过低的全景绿视率均可能不利于个体愉悦度的提升，但高低全景绿视率的转变则可有效增加个体愉悦度。因此，相较于单一的绿化场景，有规律地提高全景绿视率、营造富于变化的环境，能够有效提高个体愉悦度。

4.5 时频域分析

时频域分析法是将时间和频率联合至同一张表中，这种方式可以直观展现不同时间脑电信号的功率谱密度，并分析非稳定信号。将预处理（剔除10~30s的佩戴适应坏段数据）后的时域脑电数据经EEGLAB插件处理，以时频域图的形式呈现：横坐标为时间，纵坐标为频率，热度颜色表示脑电α值强度（事件相关频谱扰动，ERSP），颜色越接近深蓝表示α值越低，越接近棕红表示α值越高（图8）。

实验用全景视频由全景图边界卷接而成，播放时被试保持坐姿以保证脑电数据采集准确。由S1预景下的时频域图可见，前50s内，被试因好奇、期待等因素愉悦度较高（α值总体呈现黄色热度）；在最初的兴奋状态过后，时频域图呈现均匀分布态，表明该环境下α值较为稳定；当实验进行到中段160~200s时，被试视线集中至道路铺装画面，此时α值明显下降，表明VR场景中硬质基础设施的出现会降低个体愉悦度。

被试休息后依次进入S2、S3、S4和S1–2预景。因对实验有了初步了解，所以由时频域图可见，实验前数十秒被试未产生强烈情绪波动。因S2预景中植被量有所增加，α波时频域图呈现明显分段。相较于有乔木的视线区域，灌木及硬质铺装处α值较低。在S3预景中，被试整体愉悦度较高。其中，视线位于两块主要绿地时α值普遍提升（呈现黄色）；视线位于铺装区段时α值下降（呈现蓝色）。在S4预景中，由于全景绿视率过高且缺乏变化，有密林压抑感，导致其时频域图与S1预景相似，较为均匀单一。此后，当被试再次处于全景绿视率为0的S1–2预景时，愉悦感明显提升：前30s时，其α值的频域呈现棕红色热度，表明此时被试α值较高，其后表现出与S1和S4预景类似的时频域特征。表明由密林视野转变为开阔视野后，被试愉悦度会在短时间内快速提升。

4.6 脑地形图分析

由图8中的脑地形图可知，在S1预景下，被试的Fp1和Fp2（额叶）、Cz（顶叶）、P3和P4（枕叶）电极总体呈现低α值状态（以深蓝色区域为主）。随着全景绿视率的增加，脑地形图的主要变化规律包括：

1）在全景绿视率由0至60%的转变过程中，随着被试愉悦度增高，脑地形图的颜色由深蓝转为棕黄；而经历60%~90%的绿视率变化后，α值明显降低。

2）被试在体验不同的全景绿视率预景时，主导精神功能的额叶与主导视觉功能的枕叶部位α值变化明显，主导体感功能的顶叶α值变化较不明显。这表明不同全景绿视率的环境引发的脑部变化区域基本一致，额部与枕部受刺激较明显。

5 讨论与结论

本研究以VR全景技术为平台，基于脑电技术结合问卷调查构建了主客观协同分析的方法，分析了不同全景绿视率预景下个体愉悦度变化，以期探寻适宜的绿视率设计指标范围。由于全景绿视率为新近提出的研究指标，当前研究尚不深入，因此本文仅采用该概念，不涉及具体原理的探讨。研究结果显示，在全景绿视率为0的环境中，被试的愉悦度最低；在30%的全景绿视率环境中，被试的愉悦度有所提高；当全景绿视率达到60%时，愉悦度最高。该结果与郑凌予等人[41]及韩可宗[42]得出的30%~60%绿视率的植被环境评价较好的结果基本一致。因此，绿地系

统规划设计可将60%的全景绿视率作为参考指标，创造高愉悦度的绿地空间。

城市绿地系统是市民日常接触自然的重要途径，优质的绿地与林下空间可以降低精神疾病风险、有益身心健康发展[43][44]。基于生理传感与VR技术的研究也表明，即使在人工环境中，通过强化自然特性也能给人体带来疗愈效果[45]。但目前学界对过度绿化带来的健康风险研究较少。本研究发现，在全景绿视率达90%的环境中，被试的脑电愉悦度显著降低，且主观表现出压力情绪，这表明过度绿化可能导致观者产生负面情绪。此外，本研究结果也表明，交替变换的环境能够提升个体愉悦度。因此，在规划设计时交替设置不同的绿视率环境可有助于提升游览者的愉悦度。

本研究面临脑电实验样本和数据的收集难度较大、过程与处理方法复杂繁琐等困难。本研究单一实验有效被试样本量为18，与前人研究取样数基本一致[28][29][36]。在当前相关研究方兴未艾的阶段，基于实验便利性开展先期研究有是必要的，但随着研究的发展，宜尽可能平衡研究的时效性和困难度之间的矛盾，以减少不同背景被试对实验结果造成的影响。同时进一步扩大被试的职业、年龄、教育背景多样性，以更加全面地了解全景绿视率和人体愉悦度间的关系。

由于本研究中的卷积神经网络可能将树木枝干所占据的范围均识别为植被部分（即将枝叶之间的孔隙也算作植被部分），因而实验测得的全景绿视率较人工测算高约5%~15%[46]。因此，当采用卷积神经网络法计算全景绿视率时，宜选用植物枝叶密度大（如枝繁叶茂）的场景，以减少与人工测算的差异。室内VR技术克服了实地场景有限及定量模拟成本高、耗时久等困难。未来研究可进一步探究室内外环境对VR技术的影响，或提高VR技术对真实场景的还原度。此外，还可结合温湿度等其他环境因子或适当改善植物配植、栽植方式等，弥补因绿视率偏低导致的舒适度不足问题[47][48]。

问卷调研是传统且重要的研究方法，而脑电数据则可提供更为客观和定量的数据支撑。随着学科交叉的深入及生理心理监测技术的发展，可系统构建融合生理心理水平的虚拟全景体系，以更好地为可持续的城市设计提供定性和定量的参考依据，提升居民身心健康。

基金项目

· 安徽省自然科学基金项目“基于出行时空行为的城市绿地空间慢行机能优化方法研究”（编号：1908085QE209）
· 安徽省高校自然科学研究重点项目“健康运动导向的日常游憩型绿地布局优化途径研究”（编号：KJ2018A0505）
· 2020年度国家留学基金委出国留学资助项目（CSC编号：202008340054）