ORIGINAL PAPER

Physiological and psychological responses to tended plant communities with varying color characteristics

Siyuan Zheng[1] · **Yanzhen Zhou**[1] · **Haiyan Qu**[1]

Abstract Exposure to plants has been reported to promote health and reduce stress, and plant color has direct impacts on physical and mental health. We used images of common types of tended plant communities in Shenyang, China, with combinations of yellow, green, and red foliage, as experimental stimuli. A total of 27 images were used as visual stimuli. We used electroencephalography to measure α wave activity (8–13 Hz) in 40 subjects while they viewed visual stimuli. These data were combined with subjective questionnaire data to analyze the relaxing effect of images of tended plant communities with different color types and proportions on people. The results revealed that, although there were slight differences between the electroencephalography and psychological findings, women were significantly more relaxed than men after viewing the images. Physiological and psychological responses varied with the types and proportions of colors in the tended plant communities: those of foliage with combinations of two or three colors induced stronger responses than images with a single color. Specifically, (1) for one-color plant communities, green or yellow plant communities induced a stronger relaxation effect than red plant communities; (2) for two-color plant communities, the optimal color proportion was 55% + 45%, and the green + yellow and green + red color combinations induced a stronger relaxation effect; (3) for three-color plant communities, the relaxation effect was strongest when the color proportion was 55% green + 25% yellow + 20% red. These data would provide a plant color matching in future plant landscape design, which may be helpful for creating healthy and relaxing environments.

Siyuan Zheng and Yanzhen Zhou have contributed equally for this work.

The online version is available at http://www.springerlink.com
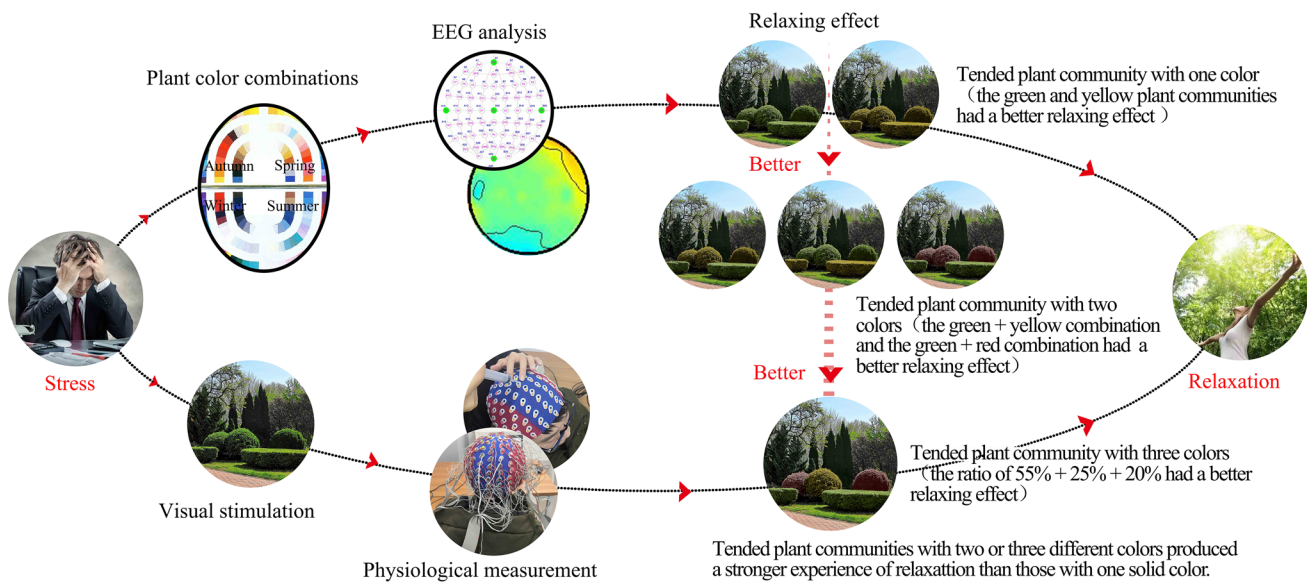
Corresponding editor: Yu Lei.

✉ Haiyan Qu
  guqujun@126.com

1 School of Architecture and Urban Planning,
   Shenyang Jianzhu University, Shenyang 110168,
   People's Republic of China

🙋 Springer

Graphical abstract

Tended plant communities with two or three different colors produced a stronger experience of relaxattion than those with one solid color.

Introduction

Vegetation is an important element of the environment and the presence of plants is vital for humans, non-human animals, and ecosystems. Numerous studies have reported that plants can improve the thermal comfort of human habitats (Abdi et al. 2020; Chen et al. 2021a, b; Narimani et al. 2022). Besides, plants adsorb particulate matter from the environment, purify the air (Shi et al. 2021), and can be used to detect the CO_2 concentration of the soil and control ecological balance (Lakkaraju et al. 2010). With the rapid development of cities, there has been an increase in the prevalence of negative emotional states, such as stress, in daily life (Peen et al. 2010). The impacts of environmental elements, such as plants, on humans and wildlife should receive more attention during urban construction. Athira et al. (2019) reported that humans and insects have different visual sensitivity to plants with different colors. The colors of plants have been reported to directly act on the human senses, producing physical and mental reactions (Berto 2007; Gao and Xin 2006). Several recent studies examined plant color in terms of aesthetic, psychological, and physiological effects on multiple scales, including plant organs (Hůla and Flegr 2016), monomers (Jang et al. 2019), and groups (Zhuang et al. 2021). Another studies have confirmed that plants with specific colors have unique effects on fatigue (Yao et al. 2020), mood (Jonauskaite et al. 2018), and emotion (Kexiu et al. 2021).

To examine the effects of plant color, questionnaire survey and subjective scale evaluation methods have been widely used in previous studies. For example, Ulrich (1984), Behe et al. (1999), Kaufman and Lohr (2004), and Shibata and Suzuki (2004) used subjective evaluation to confirm that green plants exert a positive impact on the completion of creative tasks, and can improve mood and learning efficiency. Saito (1996) reported that the use of plants with yellow flowers in interior decoration can help people maintain focus. Sinkkonen (2006), Lev-Yadun and Holopainen (2009), and Wang et al. (2020) studied color preferences for autumn foliage in terms of both the plant leaf and crown, and revealed that brightly colored foliage was preferred for autumn plants. Hůla and Flegr (2016) investigated aesthetic preferences for plant color and shape among members of the public using a subjective rating method, revealing that blue flowers and symmetrical flower shapes were rated most positively. Tomitaka et al. (2021) conducted a questionnaire survey of plant communities in natural and urban parks. The results confirmed that flower color diversity was particularly important to visitors' experiences of the park.

Table 1 Brain activity types and corresponding states

Types	Frequency (Hz)	Status
δ wave	1–4	Deep sleep
θ wave	4–8	Half-sleep
α wave	8–13	Relaxation and concentration
β wave	13–30	Nervousness or hyperactivity

Subjective evaluation is a convenient and quick experimental method. However, cross evaluation using biological measurements and subjective evaluations can more comprehensively and accurately demonstrate the effects of plant color on humans. Common physiological measurement methods include brain electroencephalography (EEG), electrocardiography (ECG), galvanic skin response (GSR), blood pressure (BP), and fingertip pulse (FP). In one previous study, Jacobs and Hustmyer (1974) studied the effects of red, yellow, blue, and green stimuli using GSR and found that red had the greatest arousal to neural stimuli, followed by green and yellow, with blue having the lowest arousal. Serra et al. (2021) studied the architectural color preferences of students of different genders and found that male students preferred orange and red buildings, whereas female students preferred pink, green, or blue buildings. Brown buildings were found to be the least popular among students regardless of gender. Using subjective ratings in combination with eye-tracking, Dupont et al. (2015; 2016) studied students' visual processing while viewing landscapes and buildings photographs. In a study of plant-related preferences, Heerwagen and Orians (1993) reported that petal shapes that were symmetrical on both sides were rated more positively. Jang et al. (2014) measured EEG in combination with a semantic questionnaire to investigate preferences for green, red, and yellow monochromatic plants, but did not systematically examine combinations of multiple plant colors.

The sampling rate of EEG can reach 2084 Hz, which represents a very high level of temporal sensitivity, and can reflect neural activity on the scale of milliseconds (Tucker et al. 1999). EEG is used in many fields, including psychology, physiology, medicine, neuroscience, artificial intelligence, environmental science, health, sports, industrial applications, and military applications to examine a variety of neural activities, including cognitive processes. Different physiological and psychological conditions can stimulate neural oscillations at specific frequencies (Stevens and Zabelina 2019). In general, the frequency of human brain oscillations produced by neural activities ranges from 1 to 30 Hz, and can be divided into four types: δ, θ, α, and β (Lutz et al. 2008; Galadí et al. 2020) (Table 1). Kiloh (1982), Kamei et al. (2000), Stinson and Arthur (2013), and Bazanova and Vernon (2014) used α waves as an index in studies of human physical and mental state, revealing that α waves are related to mental relaxation as well as physical and mental calmness.

EEG has been used to examine differences in the effects of different plant colors and species on neural activity. For example, Jang et al. (2014) used EEG to monitor the effects of five different plant colors (green radish; white, yellow, pink, and red longevity flowers) on α and β wave activity in the brain. The results indicated that green plants elicited more α wave activity and less β wave activity compared with plants of other colors (Jang et al. 2014). Fan and Niu (2014) further explored the effects of different flower colors on α and β waves in different study populations by combining subjective evaluation with EEG. The results indicated that pink, purple, and yellow flowers promoted the generation of α waves, which was associated with increased relaxation and concentration in all groups. Jap et al. (2009) conducted a driving fatigue test using EEG and found that α rhythms were often present when the driver was in a relaxed state and that the presence of β rhythms represented an increase in driver alertness. Additionally, the calculation of α/β can be used to evaluate the mental state of the driver. Because α waves are frequently used to study relaxation in humans (Kiloh 1982; Kamei et al. 2000; Stinson and Arthur 2013; Bazanova and Vernon 2014), we selected α wave power (8–13 Hz) as an indicator of EEG measurement in the present study.

Previous studies that used subjective questionnaires and EEG methods to study the effects of plants on humans mostly examined the impact of a single plant color or a specific plant color system. However, plants appear in nature as communities comprising a wide variety of colors. In a study by Thorpert et al. (2018), red, yellow, and blue cardboards were used with a background screen of green vegetation to study the effects of plants on human perception. However, few studies have explored the effects of colors in tended plant communities, particularly in terms of the physiological effects of different color combinations, proportions, and positions. Therefore, we examined the effects of the colors of common plants in nature on physical and mental health using common types of plant community combinations in Shenyang as research stimuli. In accord with previous studies, we examined the effects of various numbers of colors, color proportions, and color position distributions when one, two, and three foliage colors were present in tended plant communities. We used a subjective questionnaire and α wave data as measures of human physiology and psychology. Our hypotheses were as follows: (1) there would be a significant correlation between subjective scale evaluations and α wave data; (2) plant communities with different color types and proportions would elicit different physiological and psychological effects. Our findings may be useful for extending current understandings of plant color as a visual attribute from a human perspective and providing direction regarding visual features for future approaches to conservation and biodiversity promotion.

Materials and methods

Stimuli

Previous studies examined the influence of plants on human participants using real plants or images of plants as visual stimuli (Ulrich et al. 1991; Hull and Stewart 1992; Chang 2004; Chang and Chen 2005; Kreibig 2010). The content of the visual stimuli used in the present experiment was mainly based on common types of tended plant community in Shenyang. A Canon EOS 200D SLR camera was used to take outdoor photographs of plants between 10:00 and 14:00 while the weather was clear. The main color temperature of the plant leaves was kept relatively stable (Lee et al. 2002). During shooting, we took photographs from a height of 1.5 m with a depth of field that was consistent with an average viewing angle. The photographs were captured on the basis of the expectation that an observer would be able to view the entire panorama from 1.5 m away (Wang et al. 2018). The aspect ratio of each photograph was 3/2 or 2/3. The photography was conducted in June and lasted less than 2 weeks to avoid major seasonal changes in plant leaf color.

A total of 65 photographs of tended plant communities were captured.

The colors of plant leaves can vary according to the maturity of the leaves, differences in light exposure, varying soil conditions, and other factors. Therefore, when extracting the plant colors, the color that occurred over more than 50% of the total leaf area was considered to be the representative color of the entire plant (Wang et al. 2018). The different plant colors recorded in this survey are shown in Table 2.

Fifteen people engaged in landscape design rated the beauty of the photographs on a scale from 1 to 5, and the photograph with the highest score was selected as the experimental stimulus (Fig. 1). The photograph showed a deciduous tree + evergreen tree + shrub (ground cover) + lawn multi-layer plant community. In accord with landscape characteristics and previous research (Wang et al. 2007; Yao et al. 2012; Liu et al. 2014; Ren and Kang 2015), in a plant community that includes common evergreen trees + shrubs + ground cover, the trees typically constitute the background of the community, and the lawn serves as the foreground. Visual attention is mainly distributed in the middle ground, which includes the middle and lower layer of the community (Wang et al. 2018). In this experiment,

Table 2 Plant colors and RGB values

Plant community	Plant type	Representative plant	Plant color	RGB value
Multilayer plant community	Arbor	*Pinus tabulaeformis* Carr., *Sabina chinensis* (L.) Ant., *Platycladus orientalis* (L.) Franco		48/50/45
	Shrub	*Ligustrum obtusifolium* Sieb. et Zucc. ssp. *suave* Kitag., *Euonymus kiautshovicus* Loes., *Syringa microphylla* Diels		82/105/26
		Buxus microphylla var. koreana, *Ulmus pumila* 'Jinye', *Spiraea bumalda* 'Gold Flame'		206/187/69
		Berberis thumbergii DC. f. atropurpurea Rehd., *Physocarpus opulifolius* 'Diabolo'		78/40/36

Fig. 1 Research stimuli with research objects and proportions

Table 3 Plant communities with one, two, and three colors

Combination	Name	Proportion	Name	Proportion	Name	Proportion
One color	G^{100}	100%G	R^{100}	100%R	Y^{100}	100%Y
Two colors	$G^{55}R^{45}$	55%G+45%R	$R^{55}Y^{45}$	55%R+45%Y	$Y^{55}G^{45}$	55%Y+45%G
	$G^{55}Y^{45}$	55%G+45%Y	$R^{55}G^{45}$	55%R+45%G	$Y^{55}R^{45}$	55%Y+45%R
Three colors	$G55\% + Rx\% + Y(45-x)\%$		$R55\% + Yx\% + G(45-x)\%$		$Y55\% + Gx\% + R(45-x)\ \%$	
	$G^{55}R^{10}Y^{35}$	55%G+10%R+35%Y	$R^{55}Y^{10}G^{35}$	55%R+10%Y+35%G	$Y^{55}G^{10}R^{35}$	55%Y+10%G+35%R
	$G^{55}R^{15}Y^{30}$	55%G+15%R+30%Y	$R^{55}Y^{15}G^{30}$	55%R+15%Y+30%G	$Y^{55}G^{15}R^{30}$	55%Y+15%G+30%R
	$G^{55}R^{20}Y^{25}$	55%G+20%R+25%Y	$R^{55}Y^{20}G^{25}$	55%R+20%Y+25%G	$Y^{55}G^{20}R^{25}$	55%Y+20%G+25%R
	$G^{55}R^{25}Y^{20}$	55%G+25%R+20%Y	$R^{55}Y^{25}G^{20}$	55%R+25%Y+20%G	$Y^{55}G^{25}R^{20}$	55%Y+25%G+20%R
	$G^{55}R^{30}Y^{15}$	55%G+30%R+15%Y	$R^{55}Y^{30}G^{15}$	55%R+30%Y+15%G	$Y^{55}G^{30}R^{15}$	55%Y+30%G+15%R
	$G^{55}R^{35}Y^{10}$	55%G+35%R+10%Y	$R^{55}Y^{35}G^{10}$	55%R+35%Y+10%G	$Y^{55}G^{35}R^{10}$	55%Y+35%G+10%R

the objects to which we applied color treatment were the plants in the middle of the landscape, namely, a hedgerow positioned lower in the image, and ball-shaped bushes positioned in the upper portion of the image. The areas of the different plants (out of a total of 100% for all plants) were 10%, 10%, 20%, and 15% for the ball-shaped bushes, and 10% and 45%, for the hedgerow, as shown in Fig. 1. We used Photoshop CS6 software to process the colors of the plants in the middle of the scene to construct combinations of different color types, ratios, and positions. We generated a total of 27 images for use as experimental stimuli.

Table 3 shows the combination form of plant community colors and proportions in all stimulus materials. "One color" shows the 3 stimuli in which the plants in the middle of the scene were all a single color. The color ratios of the images were either 100% red, 100% yellow, or 100% green. "Two colors" shows the 6 stimuli in which there were combinations of two colors. When the lower layer of the hedge was green, red, or yellow, the color of the spherical shaped bushes was changed so that the color proportion was 55%+45%. "Three colors" shows the 18 stimuli that contained combinations of three colors. The lower layer of the hedge was fixed to green, red, or yellow, and the color of the three ball-shaped bushes in the upper part of the image were changed. The red, green, and yellow combinations had a color ratio of 55% (lower hedgerows) and $x\%$, $(45-x)\%$ (upper ball-shaped bushes), where x was assigned a value of 10, 15, 20, and two-by-two combinations of 25, 30, or 35, respectively. The stimulus material was modified as follows using this approach.

$$G55\% + Rx\% + Y(45-x)\% \tag{1}$$

The lower layer of the hedges was fixed to green, accounting for 55% of the area of the manipulated part of the image, and the colors of the other bushes were individually changed to red or yellow. By changing the colors of the spherical shrubs, the proportion of red in the manipulated part of the image was 10%, 15%, 20%, 25%, 30%, and 35%, while that of yellow was 35%, 30%, 25%, 20%, 15%, and 10%. This method was used to produce six stimulation images.

$$R55\% + Yx\% + G(45-x)\% \tag{2}$$

The lower layer of the hedges was fixed to red, which accounted for 55% of the area of the manipulated part of the image, and the colors of the other bushes were individually changed to green or yellow. By changing the colors of the spherical shrubs, the proportions of green in the manipulated part of the image were 10%, 15%, 20%, 25%, 30%, and 35%, whereas the proportions of yellow were 35%, 30%, 25%, 20%, 15%, and 10%. This produced six stimulation images.

$$Y55\% + Gx\% + R(45-x)\% \tag{3}$$

Fig. 2 EEG cap and electrode placement

The lower layer of the hedges was fixed to yellow, accounting for 55% of the area of the manipulated part of the image, and the colors of the other bushes were changed to green and red individually. By changing the colors of the spherical shrubs, the proportions of green in the manipulated parts of the image were 10%, 15%, 20%, 25%, 30%, and 35%, while the proportions of red were 35%, 30%, 25%, 20%, 15%, and 10%. This method was used to produce six stimulation images.

Study periods and settings

The experiment was conducted at the Landscape Architecture Laboratory from 9:00 to 11:00 and 15:00 to 16:30 every day in November and December 2019. The room was 5-m long, 3.8-m wide, and 3-m high. The walls were pure white, and the interior was lit with incandescent lamps (65 lux). During the test, the indoor temperature and relative humidity

were maintained to ensure somatosensory comfort. We also attempted to maintain consistency regarding external factors, such as sound, in each experimental trial. Furthermore, throughout the experimental process, we attempted to ensure that there was no electromagnetic interference.

Participants

We recruited a total of 40 undergraduates and postgraduates (20 men and 20 women), with an average age of 21.83 ± 2.72. Because of the high efficiency and low cost of accessing university students, this sampling approach is widely used by researchers in studies using experience evaluation (Zhao et al. 2018). Before the experiment, participants were required to have no mental illness, physical illness, or history of drug abuse, and all were right-handed. Subjects were required to wash their hair before the experiment to facilitate EEG measurement, and to avoid drinking
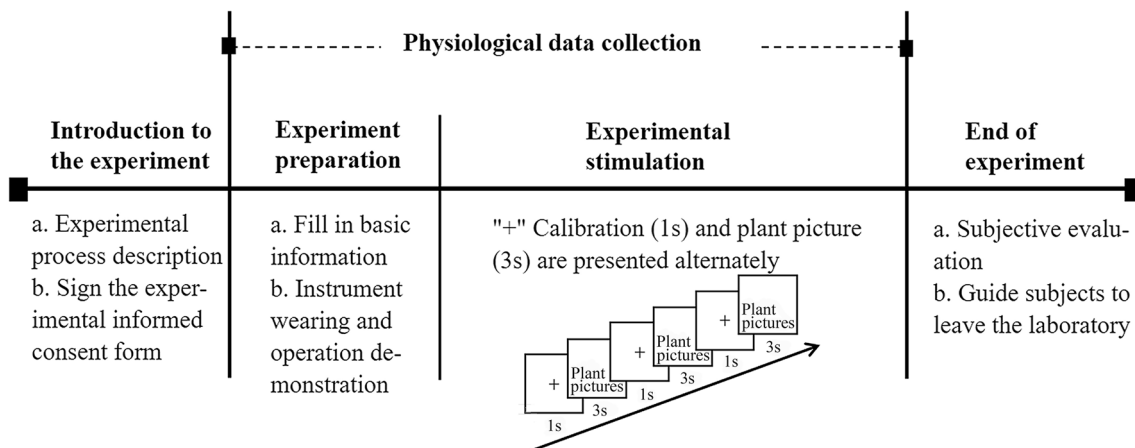

Fig. 3 Flow chart of the experimental protocol

alcohol, smoking, or drinking caffeinated beverages prior to the experiment.

Procedure

Each participant was asked to sit on a comfortable chair positioned 0.6 m away from the computer screen, and to adjust their sitting posture so that their eyes were at the same level as the screen. All other equipment was positioned 1 m behind the subject, and interference from other instruments was minimized. Subjects were informed about the experimental purpose and process. Participants provided personal information via an informed consent form, which they signed to declare that they voluntarily participated in the experiment. Participants were told that they could withdraw from the experiment at any time if they were uncomfortable. We ensured that personal physiological and psychological data were kept strictly confidential. This study was approved by the ethical committee of the School of Architecture and Urban Planning, Shenyang Jianzhu University, China.

The experimenter explained and demonstrated the experimental procedures and the use of the instruments to the subjects. The experimenter then applied EEG electrode gel and fitted the participants for EEG signal acquisition. Classical music (Pachelbel's "Canon and Gigue in D") was played to help participants relax and adapt to the experimental environment as quickly as possible. We used the Active Two biopotential measurement and analysis system (BioSemi, Netherlands) to measure EEG. The EEG signals were detected by electrodes in an electrode cap, which made contact with the scalp via EEG electrode gel (Fig. 2). There were 128 acquisition channels, and the data were processed using the whole brain average as a reference to avoid imbalances caused by incorrectly functioning electrodes. EEG electrodes were placed in accordance with international standard 10–20 system. The sampling frequency of this system was 2048 Hz, which is more accurate than that of conventional physiological monitoring equipment (typically 250, 500 or 1000 Hz). The collected EEG signals were amplified by an AC-BOX and transmitted to the recording computer for storage and analysis.

The presentation of visual stimuli during the experiment was controlled using E-prime software (Psychology Software Tools, USA), which is widely used for cognitive experiments involving EEG (Wang 2019). In each trial, a description of the task first appeared on the screen. When the participant was ready, they were expected to press the Enter button, at which point the experiment officially began. The experimental trials were divided into three sections, with 18 images in each (nine plant images alternating with nine images of a blank space with a " + " symbol in the center of the screen). The stimuli were displayed for 3 s (Atkinson and Campos 2016), and

Table 4 Correlation analysis of subjective evaluations and physiological data

Variable	Statistics	Subjective questionnaire
Physiological data (α wave)	Pearson correlation	0.389*
	Significance (bilateral)	0.045
	N	40

*Significant correlation at the 0.05 level (bilateral)

the images with the " + " were displayed for 1 s (Robins and Hollands 2017). The " + " served to help the subjects focus their attention and calibrate their visual focus. After viewing all of the stimuli, the subjects were asked to complete a subjective questionnaire. To overcome the effects of experimental order, each set of photographs of plant colors was presented in a random configuration. The total duration of the experiment was approximately 40 min (the detailed experimental process is shown in Fig. 3).

Data analysis

Data processing of α wave activity and subjective evaluation scores

The data processing was conducted in two parts for EEG and subjective questionnaire data analysis. In accord with the different regions of the brain, α wave activity was extracted from the collected EEG signals of the occipital lobe related to visual processing. Prior to this procedure, data preprocessing using MATLAB was used to remove artifacts, including those caused by eye movements, power frequency interference, and electromagnetic interference in the experimental environment. Data preprocessing operations included BioSemi electrode positioning, removal of ineffective electrodes according to the channel range, filtering (removing 0.5–30 Hz band-pass filter, then removing 48–52 Hz interference with a notch filter), reducing the sampling rate, re-referencing, and removing artifacts, and finally extracting the independent segmentation of each marker task. The preprocessed data were based on MATLAB platform to create a study. Data were imported in batches for intra-group analysis, and α wave power was calculated.

The subjective questionnaire was designed on the basis of a Likert scale (Barone 2005; Li 2013), and was used to measure subjects' emotional state. The questionnaire contained positive attitude statements ("comfortable" and "relaxed") and participants were asked to indicate whether they very much agreed, agreed, were uncertain, disagreed, or very much disagreed with the statements by providing a score of 5, 4, 3, 2, or 1 points, respectively, for each item. The questionnaire was designed on the basis of the tended plant community's color composition (one, two, and three

colors). Taking different color combinations and different color proportions as units, the scores of 40 questionnaires were calculated as mean and standard deviation for further analysis.

Table 5 Gender-related differences in α wave power and subjective evaluation scores when observing plant communities containing one

Pictures	Gender	N	α wave		Subjective evaluation scores	
			Mean + SE	p-value (both sides)	Mean + SE	p-value (both sides)
One color	Male	20	33.70 ± 0.09	< 0.0001**	2.55 ± 0.19	0.162
	Female	20	35.19 ± 0.12		2.93 ± 0.19	
Two colors	Male	20	33.48 ± 0.07	< 0.0001**	3.25 ± 0.09	0.691
	Female	20	35.57 ± 0.08		3.35 ± 0.09	
Three colors	Male	20	33.94 ± 0.04	< 0.0001**	2.84 ± 0.07	0.004**
	Female	20	35.44 ± 0.05		3.12 ± 0.07	
Total	Male	20	33.81 ± 0.03	< 0.0001**	2.90 ± 0.05	0.002**
	Female	20	35.44 ± 0.04		3.15 ± 0.06	

**Indicates that the correlation reached a very significant level ($p < 0.01$)

Table 6 Gender-related differences in α wave power and subjective evaluation scores when viewing plant communities containing one color

Pictures	Gender	N	α wave		Subjective evaluation scores	
			Mean + SE	p-value (both sides)	Mean + SE	p-value (both sides)
G^{100}	Male	20	33.74 ± 0.17	< 0.0001**	3.27 ± 0.24	0.299
	Female	20	35.47 ± 0.22		3.56 ± 0.29	
R^{100}	Male	20	33.50 ± 0.16	< 0.0001**	1.45 ± 0.16	0.042*
	Female	20	34.90 ± 0.18		2.25 ± 0.31	
Y^{100}	Male	20	33.86 ± 0.15	< 0.0001**	2.73 ± 0.24	0.576
	Female	20	35.21 ± 0.21		2.89 ± 0.31	

**Indicates that the correlation reached a very significant level ($p < 0.01$), and * indicates that the correlation reached a significant level ($p < 0.05$)

Table 7 Gender-related differences in α waves and subjective evaluation scores when viewing plant communities containing two colors

Pictures	Gender	N	α wave		Subjective evaluation score	
			Mean + SE	p-value (both sides)	Mean + SE	p-value (both sides)
$G^{55}R^{45}$	Male	20	32.97 ± 0.15	< 0.0001**	3.33 ± 0.26	0.701
	Female	20	35.23 ± 0.20		3.55 ± 0.16	
$G^{55}Y^{45}$	Male	20	33.75 ± 0.15	< 0.0001**	3.62 ± 0.21	0.972
	Female	20	35.50 ± 0.17		3.73 ± 0.29	
$R^{55}Y^{45}$	Male	20	33.30 ± 0.17	< 0.0001**	2.83 ± 0.17	0.563
	Female	20	35.29 ± 0.19		2.82 ± 0.12	
$R^{55}G^{45}$	Male	20	33.92 ± 0.17	< 0.0001**	3.00 ± 0.26	0.157
	Female	20	35.74 ± 0.20		3.45 ± 0.21	
$Y^{55}G^{45}$	Male	20	33.62 ± 0.16	< 0.0001**	3.54 ± 0.22	0.948
	Female	20	35.71 ± 0.18		3.64 ± 0.20	
$Y^{55}R^{45}$	Male	20	33.31 ± 0.15	< 0.0001**	2.92 ± 0.19	0.936
	Female	20	35.94 ± 0.17		3.00 ± 0.30	

**Indicates that the correlation reached a very significant level ($p < 0.01$)

Statistical analysis

Statistical analysis was completed using IBM SPSS V21.0. We used one-way ANOVA to examine the physiological and psychological differences caused by the different stimulus images. If the dataset did not exhibit homogeneity of variance, we used the Kruskal–Wallis test to further compare the physiological and psychological differences caused by different visual stimuli. We used correlation analysis to explore the correlations between the questionnaire data and the α wave data.

All charts in this experiment were constructed using MATLAB, SPSS v21.0, Origin 8.5 (Origin Lab, Corp., Northampton, MA, USA), or Photoshop cs6 (Adobe, Inc., Mountain View, CA, USA).

Table 8 Gender-related differences in α waves and subjective evaluation scores when viewing plant communities with three colors

Pictures	Gender	N	α wave		Subjective evaluation scores	
			Mean + SE	p-value (both sides)	Mean + SE	p-value (both sides)
$G^{55}R^{10}Y^{35}$	Male	20	34.68 ± 0.17	0.214	2.87 ± 0.29	0.740
	Female	20	34.90 ± 0.19		3.00 ± 0.30	
$G^{55}R^{15}Y^{30}$	Male	20	33.86 ± 0.16	<0.0001**	3.07 ± 0.27	0.325
	Female	20	35.00 ± 0.21		3.45 ± 0.28	
$G^{55}R^{20}Y^{25}$	Male	20	33.77 ± 0.15	<0.0001**	3.54 ± 0.24	0.926
	Female	20	35.82 ± 0.19		3.57 ± 0.23	
$G^{55}R^{25}Y^{20}$	Male	20	33.31 ± 0.17	<0.0001**	3.26 ± 0.29	0.834
	Female	20	35.61 ± 0.21		3.25 ± 0.33	
$G^{55}R^{30}Y^{15}$	Male	20	34.25 ± 0.17	<0.0001**	2.36 ± 0.24	0.152
	Female	20	35.55 ± 0.21		3.00 ± 0.38	
$G^{55}R^{35}Y^{10}$	Male	20	34.03 ± 0.17	<0.0001**	2.42 ± 0.29	0.292
	Female	20	35.00 ± 0.21		2.83 ± 0.30	
$R^{55}Y^{10}G^{35}$	Male	20	34.06 ± 0.16	0.029*	2.57 ± 0.25	0.272
	Female	20	35.47 ± 0.20		3.00 ± 0.30	
$R^{55}Y^{15}G^{30}$	Male	20	33.53 ± 0.16	0.021*	2.83 ± 0.30	0.546
	Female	20	35.37 ± 0.19		3.09 ± 0.32	
$R^{55}Y^{20}G^{25}$	Male	20	34.00 ± 0.17	<0.0001**	2.71 ± 0.27	0.123
	Female	20	35.58 ± 0.20		3.33 ± 0.28	
$R^{55}Y^{25}G^{20}$	Male	20	34.00 ± 0.17	<0.0001**	2.46 ± 0.24	0.078
	Female	20	35.58 ± 0.19		3.17 ± 0.30	
$R^{55}Y^{30}G^{15}$	Male	20	33.88 ± 0.17	<0.0001**	2.77 ± 0.28	0.440
	Female	20	35.65 ± 0.21		3.09 ± 0.32	
$R^{55}Y^{35}G^{10}$	Male	20	34.04 ± 0.17	<0.0001**	2.18 ± 0.34	0.421
	Female	20	35.39 ± 0.20		2.22 ± 0.22	
$Y^{55}G^{10}R^{35}$	Male	20	33.87 ± 0.15	0.030*	1.82 ± 0.12	0.047*
	Female	20	34.92 ± 0.19		2.40 ± 0.27	
$Y^{55}G^{15}R^{30}$	Male	20	33.39 ± 0.17	<0.0001**	2.36 ± 0.34	0.249
	Female	20	35.26 ± 0.21		2.89 ± 0.35	
$Y^{55}G^{20}R^{25}$	Male	20	34.23 ± 0.17	<0.0001**	3.13 ± 0.26	0.583
	Female	20	35.69 ± 0.20		3.33 ± 0.28	
$Y^{55}G^{25}R^{20}$	Male	20	34.29 ± 0.15	0.043*	3.17 ± 0.30	0.329
	Female	20	35.38 ± 0.19		3.54 ± 0.24	
$Y^{55}G^{30}R^{15}$	Male	20	33.74 ± 0.15	<0.0001**	3.53 ± 0.21	0.977
	Female	20	35.79 ± 0.19		3.54 ± 0.24	
$Y^{55}G^{35}R^{10}$	Male	20	34.01 ± 0.19	<0.0001**	3.06 ± 0.25	0.869
	Female	20	35.76 ± 0.22		3.00 ± 0.36	

**Indicates that the correlation reached a very significant level ($p < 0.01$), and *indicates that the correlation reached a significant level ($p < 0.05$)

Results and analysis

Correlation between subjective evaluation and physiological data

As shown in Table 4, the subjective questionnaire scores showed a significant ($p < 0.05$) positive relationship with physiological data. Therefore, we conducted further analysis of 27 images of tended plant communities with different color combinations and proportions using subjective evaluation and EEG α activity physiological data.

Brain activity and subjective evaluation scores of color combinations by gender

Plant communities with one, two, and three colors

Table 5 showed the α wave power and subjective ratings of men and women when viewing the flora, for different color combinations and across all stimuli. Female participants exhibited higher scores after viewing different color combinations of flora compared with male participants, and exhibited differences in specific characteristics. The α power was significantly higher in female participants compared with male participants for all three color combinations, and in the overall analysis ($p < 0.0001$; very significant difference). Specifically, women produced higher α wave power after viewing plants with two and three color combinations compared with monochromatic plants. Men exhibited higher α wave power when viewing monochromatic and trichromatic plant combinations compared with two-color plant

combinations. We obtained similar results in the analysis of subjective ratings. Female participants reported higher ratings than the ratings given by men when viewing plants with different color combinations, and significant gender differences emerged when viewing tricolored plant compositions ($p < 0.01$; very significant difference). This finding indicates that women were more relaxed than men after viewing the flora images containing different color combinations of green, yellow and red.

Single-color plant communities

We conducted further detailed analyses of the color ratio of different images. Table 6 shows the results for plant images containing one color, for which the color ratio was 100%. We observed a significant difference in α wave power between men and women when viewing the plant stimuli with one color ($p < 0.0001$). Moreover, after viewing three images of plant communities with one color, α wave power was significantly greater in women compared with men. Additionally, subjective ratings were higher in females compared with males, and significant differences emerged when viewing red plants ($p < 0.05$). This finding suggests that women were more relaxed than men.

Plant communities containing two colors

Table 7 shows the results for plant communities containing two colors (color ratio of 55%+45%). We found a very significant difference in α wave power between men and women
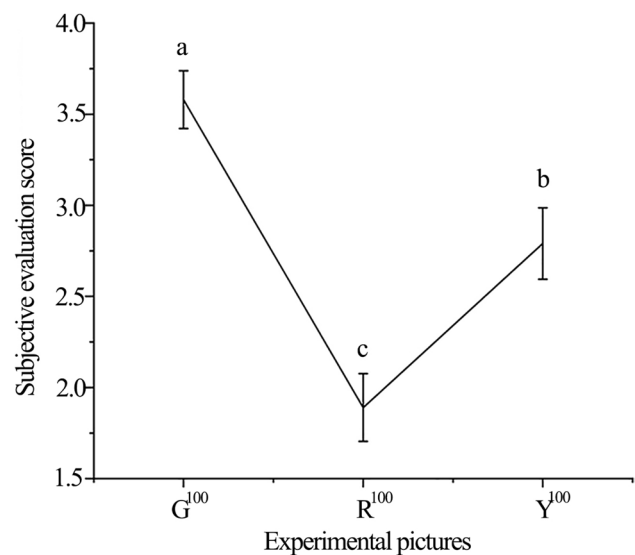

Fig. 4 Subjective evaluation scores when observing one-, two-, and three-color plant communities. *Note* Subjective evaluation scores marked with different letters were shows significant difference between color characteristic ($p < 0.05$)

Fig. 5 Subjective evaluation scores when viewing plant communities containing one color. *Note* Subjective evaluation scores marked with different letters were shows significant difference between color characteristic ($p < 0.05$)
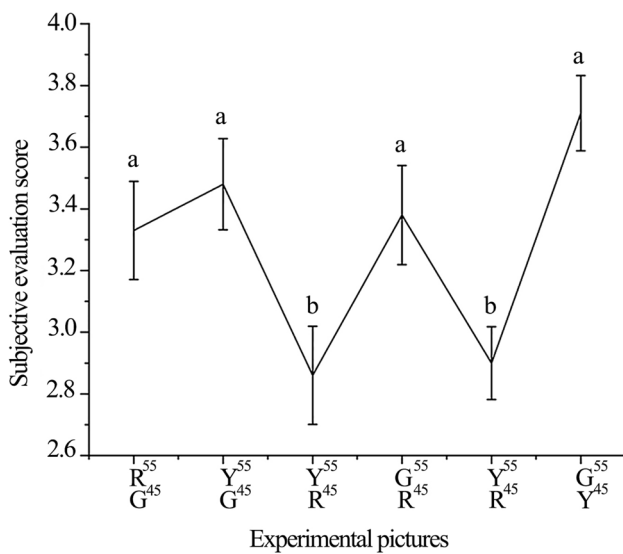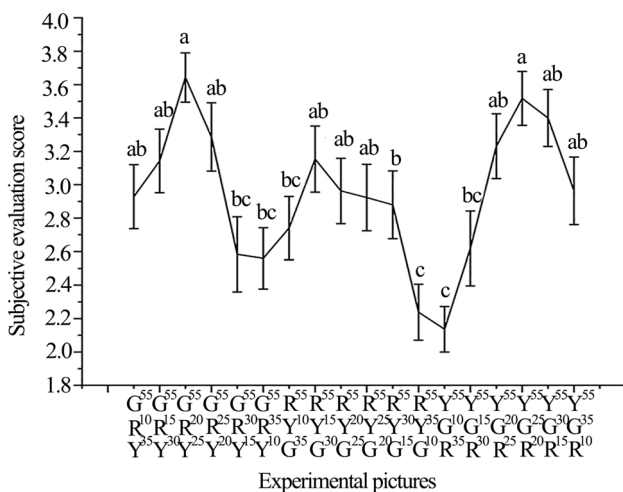
Fig. 6 Subjective evaluation scores when viewing plant communities containing two colors. *Note* Subjective evaluation scores marked with different letters were shows significant difference between color characteristic ($p < 0.05$)

when viewing plant communities containing two colors ($p < 0.0001$). Furthermore, after viewing six images of plant communities containing two colors, the α wave power in women was significantly stronger than that in men. This trend was also found in the analysis of subjective ratings, in which women generally gave higher ratings than men, although no significant differences were observed ($p > 0.05$). This finding indicates that women tended to be more relaxed than the men when viewing images of plant communities.

Fig. 7 Subjective evaluation score when viewing plant communities with three color combinations. *Note* Subjective evaluation scores marked with different letters were shows significant difference between color characteristic ($p < 0.05$)

Plant communities with three colors

Table 8 shows the results for plant communities with three colors, in which the proportion of the three colors was $G55\% + Rx\% + Y(45 - x)\%$, $R55\% + Yx\% + G(45 - x)\%$, or $Y55\% + Gx\% + R(45 - x)\%$ (according to the fixed color of the lower hedge). When the color ratios and positions were changed, we observed significant differences in the power values of α waves between men and women after viewing 18 images ($p < 0.05$). Specifically, the α wave power was significantly higher in women compared with men, which indicates that the women felt more relaxed than men after viewing the stimuli. Subjective ratings were generally higher for women compared with men, and a significant difference was seen in this combination of $Y^{55}G^{10}R^{35}$ ($p < 0.05$). This finding also suggests that women were more relaxed after viewing different proportions of the tricolor plant combination compared with men.

Subjective evaluation of different color combinations

Plant communities with one, two, and three colors

With the number of colors as the independent variable, we analyzed and compared the subjective evaluation scores of the plant communities with one, two, and three colors (Fig. 4), and found that the scores for the plant communities containing two colors (3.28 ± 0.06) were highest, and were significantly different to those for plant communities containing one (2.75 ± 0.14) and three colors (2.97 ± 0.05) ($F = 7.02$, $p < 0.01$). The scores for single-color plant
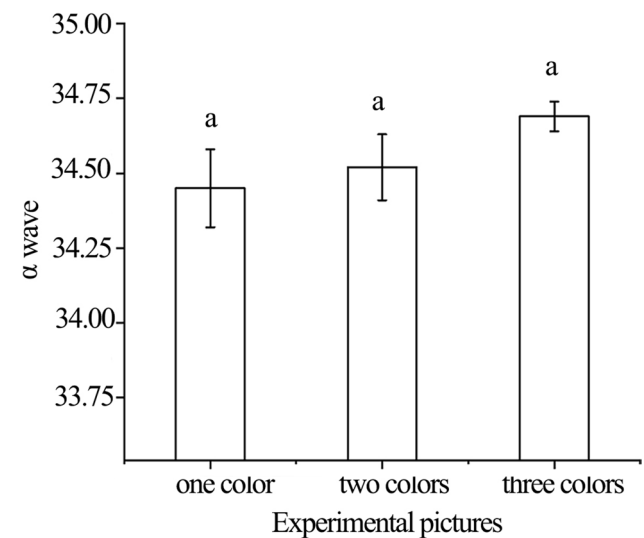

Fig. 8 α wave power when viewing plant communities with one, two, and three colors. *Note* α wave power marked with different letters were shown significant difference between each color characteristic ($p < 0.05$)
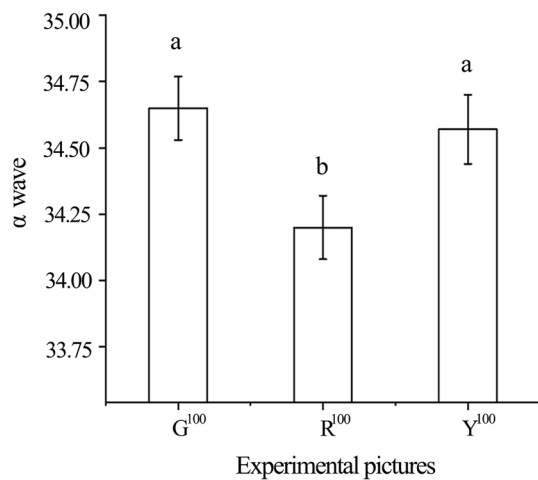
Fig. 9 α wave power when viewing plant communities containing one color. *Note* α wave power marked with different letters were shown significant difference between each color characteristic ($p < 0.05$)

communities were the lowest. Thus, the number of colors of plant communities affected the relaxation effect when subjects observed images, and the strongest relaxation effect was found for plant communities containing two colors.

Single-color plant community

The objects of the study (i.e., the bushes in the middle section of the photograph) were processed so that they only contained one color. We constructed three stimulus images: one containing red foliage, one containing yellow foliage, and one containing green foliage. The subjective evaluation results are shown in Fig. 5. There were significant differences in subjective evaluations between each of the plant communities containing single colors (F = 18.03, $p < 0.05$). Among them, the relaxation experience scores were highest for green plant communities (3.58 ± 0.16), and lowest for red plant communities (1.89 ± 0.19).

Plant communities containing two colors

Regarding subjective evaluation of plant communities containing two colors, we analyzed and compared six pictures of green, red, and yellow plant communities. As shown in Fig. 6, the plant community score was highest for $G^{55}Y^{45}$ (3.71 ± 0.12), and there was no significant difference compared with $R^{55}G^{45}$ (3.33 ± 0.16), $Y^{55}G^{45}$ (3.48 ± 0.15), and $G^{55}R^{45}$ (3.38 ± 0.16) ($p > 0.05$), whereas the subjective scores of $Y^{55}R^{45}$ (2.86 ± 0.16) and $R^{55}Y^{45}$ (2.90 ± 0.12) were significantly lower ($p < 0.05$). The results revealed
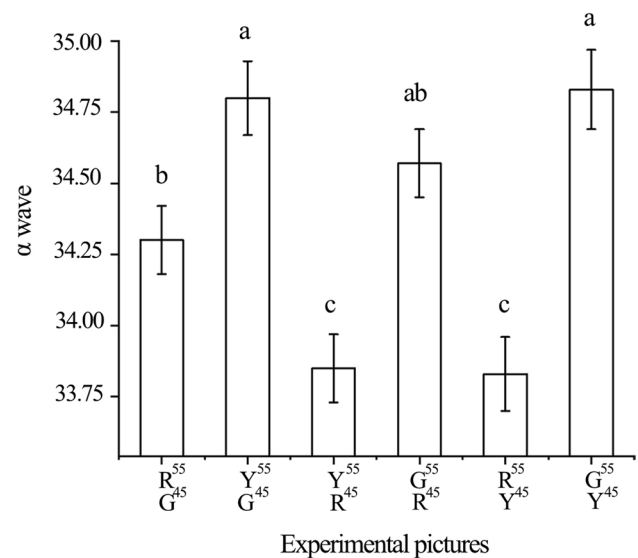

Fig. 10 α wave power when viewing plant communities containing two colors. *Note* α wave power marked with different letters were shown significant difference between each color characteristic ($p < 0.05$)

that the relaxation effect was strongest for the green + yellow combination of plant communities, and weakest for the yellow + red combination. In addition, when the plant community contained two-color combinations of green + red or green + yellow, the relaxation effect increased with the proportion of green.

Plant communities containing three colors

The results of the subjective evaluation when changing the proportions of the three colors are shown in Fig. 7. $G^{55}R^{20}Y^{25}$ (3.64 ± 0.15) had the highest subjective score, followed by $Y^{55}G^{25}R^{20}$ (3.52 ± 0.16). And, they were significantly different from the subjective evaluation scores of $G^{55}R^{30}Y^{15}$ (2.58 ± 0.23), $G^{55}R^{35}Y^{10}$ (2.56 ± 0.18), $R^{55}Y^{10}G^{35}$ (2.74 ± 0.19), $R^{55}Y^{30}G^{15}$ (2.88 ± 0.20), $R^{55}Y^{35}G^{10}$ (2.24 ± 0.17), $Y^{55}G^{10}R^{35}$ (2.14 ± 0.14) and $Y^{55}G^{15}R^{30}$ (2.62 ± 0.22) ($p < 0.05$). The scores of $R^{55}Y^{35}G^{10}$ and $Y^{55}G^{10}R^{35}$ were the lowest. Thus, the results indicated that the relaxation effect was strongest in the three-color plant community with 75% of green + yellow, and the optimal relaxation effect was observed when the green proportion was 55%. When the lower shrub was red, the relaxation effect was relatively strong if the proportions of yellow and green were balanced, or if the proportion of green was higher. Besides, when yellow and
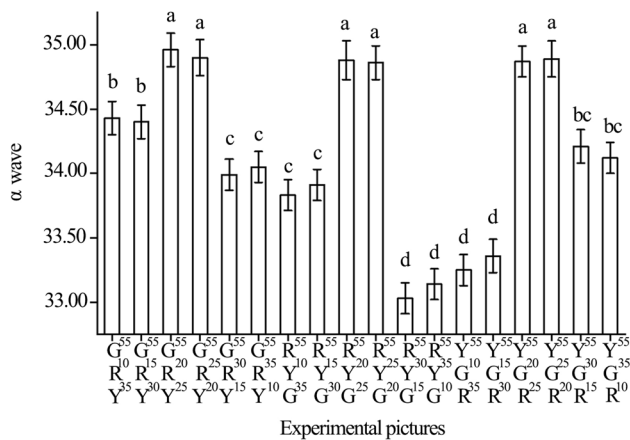
Fig. 11 α wave power when viewing plant communities with three color combinations. *Note* α wave power marked with different letters were shown significant difference between each color characteristic ($p < 0.05$)
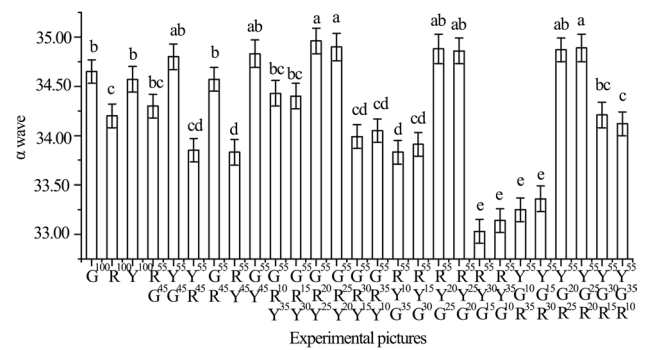

Fig. 12 Comprehensive comparison of plant communities with different color combinations. *Note* α wave power marked with different letters were shown significant difference between each color characteristic ($p < 0.05$)

red accounted for 90% of the foliage in the image, the relaxation effect was weakest.

Effects of different color combinations on brain activity

Plant communities containing one, two, and three colors

The α wave power of plant communities containing different numbers of colors (one, two, and three colors) was analyzed as a whole. Figure 8 shows that single-color (34.45 ± 0.13) plant communities had the lowest α wave power followed by two-color (34.52 ± 0.11) plant communities. The highest α wave power was observed for three-color plant communities (34.69 ± 0.05). Overall, there was no significant difference between the three types of images. Therefore, to understand the effects of different color combinations of plant communities on α wave power, it was necessary to further compare and analyze the α wave power of 27 images with different color proportions.

Single color plant community

The EEG results are shown in Fig. 9. We found significant differences in EEG α waves when participants viewed different colored stimuli ($F = 3.74$, $p < 0.05$). The strongest α wave activity occurred when viewing the green stimulus image G^{100} (34.65 ± 0.12), and the weakest occurred when viewing the red stimulation image R^{100} (34.20 ± 0.12). There were no significant differences in α wave activity between images containing green and yellow Y^{100} (34.57 ± 0.13). This indicates that green and yellow plant communities exerted stronger relaxation effects compared with red plant communities.

Plant communities containing two colors

Analysis of the EEG data generated while viewing the six stimulus images (plant communities containing two colors) revealed significant differences in α wave power ($F = 12.59$, $p < 0.0001$) (shown in Fig. 10). The strongest α wave activity was elicited by green-yellow $G^{55}Y^{45}$ (34.83 ± 0.14) images, although this was not significantly different from yellow-green $Y^{55}G^{45}$ (34.80 ± 0.13) images or green–red $G^{55}R^{45}$ (34.57 ± 0.12) images ($p > 0.05$). The weakest α wave activity was elicited by red-yellow $R^{55}Y^{45}$ (33.83 ± 0.13) images, although this was not significantly different from yellow–red $Y^{55}R^{45}$ (33.85 ± 0.12) images ($p > 0.05$). Intermediate α wave power was elicited by the green–red $R^{55}G^{45}$ (34.30 ± 0.12) image. In plant communities with two colors, the green + yellow combination and the green + red combination exerted stronger relaxation effects, as indicated by α wave power, compared with the yellow + red combination. Furthermore, the green + yellow combination induced relaxation regardless of the position or proportion of the colors. However, for the combination of green + red, the effects depended on the positions of the colors and the proportional relationships among colors. The data indicated that relaxation was maximal when green foliage was positioned in the foreground of the image, red foliage was located further back, and the proportion of green was relatively high.

Plant communities containing three colors

Figure 11 shows the results of our EEG analysis for the 18 stimulus images (plant communities containing combinations of three colors). The α wave activity induced by the 18 stimulus images was significantly different ($F = 27.20$, $p < 0.001$). The strongest α wave activity was observed for $G^{55}R^{20}Y^{25}$ (34.96 ± 0.13), followed by $G^{55}R^{25}Y^{20}$ (34.90 ± 0.14), $Y^{55}G^{25}R^{20}$ (34.89 ± 0.14),

$R^{55}Y^{20}G^{25}$ (34.88 ± 0.15), $Y^{55}G^{20}R^{25}$ (34.87 ± 0.12), and $R^{55}Y^{25}G^{20}$ (34.86 ± 0.13) images, although these were not significantly different ($p > 0.05$). The weakest α wave activity was observed for $R^{55}Y^{30}G^{15}$ (33.03 ± 0.12), $R^{55}Y^{35}G^{10}$ (33.14 ± 0.12), $Y^{55}G^{15}R^{30}$ (33.36 ± 0.12), and $Y^{55}G^{10}R^{35}$ (33.25 ± 0.12) images, with no significant differences ($p > 0.05$). $G^{55}R^{10}Y^{35}$ (34.43 ± 0.13), $G^{55}R^{15}Y^{30}$ (34.40 ± 0.13), $Y^{55}G^{30}R^{15}$ (34.21 ± 0.13), $Y^{55}G^{35}R^{10}$ (34.12 ± 0.12), $G^{55}R^{35}Y^{10}$ (34.05 ± 0.12), $G^{55}R^{30}Y^{15}$ (33.99 ± 0.12), $R^{55}Y^{15}G^{30}$ (33.91 ± 0.12), and $R^{55}Y^{10}G^{35}$ (33.83 ± 0.12) images induced intermediate α wave strength, with no significant differences.

Overall, α wave power was the strongest for plant communities with three colors, and the relaxation effect was strongest with a plant community color configuration ratio of 55% + 25% + 20%. The plant communities that produced the highest α power were those with green and yellow hedges in the lower layer, and lower proportions of red. The red + yellow and red + green configuration ratio were similar, and the positional relationship was symmetrical, with a balanced color configuration. The plant communities that produced that second-strongest α wave power had an allocation ratio of green + yellow and green + red that was greater than 85% in scenes with three colors. The α wave power was weakest, with the weakest relaxation effect, for plant communities with more than 85% yellow + red. The red and yellow plants were located in the lower layer and the allocation ratio for these colors was largest. The allocation proportion of the spherical bushes in terms of yellow + green or red + green in the upper layer was also relatively unbalanced. When the three colors were combined in one plant community, the image became more complex in that there was not only a proportional relationship between the colors but also a positional distribution and equilibrium relationship.

Images with one, two, and three colors

A comprehensive analysis of the EEG data of 27 stimulus images was performed, comparing the EEG data of images with one, two, and three colors. The results are shown in Fig. 12. There were significant differences in α wave power among the 27 stimulus images (F = 21.38, $p < 0.0001$). The strongest α wave power was induced by images with three colors $G^{55}R^{20}Y^{25}$ (34.96 ± 0.13), followed by $G^{55}R^{25}Y^{20}$ (34.90 ± 0.14), $Y^{55}G^{25}R^{20}$ (34.89 ± 0.14), $Y^{55}G^{20}R^{25}$ (34.87 ± 0.12), $R^{55}Y^{20}G^{25}$ (34.88 ± 0.15), and $R^{55}Y^{25}G^{20}$ (34.86 ± 0.13), and images with two colors, including green-yellow $G^{55}Y^{45}$ (34.83 ± 0.14) and yellow-green $Y^{55}G^{45}$ (34.80 ± 0.13). The weakest α wave power was elicited by image $R^{55}Y^{30}G^{15}$ (33.03 ± 0.12), which was not significantly different ($p > 0.05$) from $R^{55}Y^{35}G^{10}$ (33.14 ± 0.12), $Y^{55}G^{15}R^{30}$ (33.36 ± 0.12), and $Y^{55}G^{10}R^{35}$ (33.25 ± 0.12) images. These data indicate that plant communities with two or three different colors induced a stronger relaxation effect compared with those with one color. Among the 2–3 types of color combinations, the relaxation effect was strongest when the color allocation ratio was 55% + 25% + 20%, which represents an even color distribution among the different plants in relation to area. The relaxation effect was weakest when the color allocation of yellow + red exceeded 85%.

Discussion

Gender-related differences

In the current study, we used a subjective questionnaire and EEG measurement of α wave activity data as experimental indicators. We examined differences between these subjective and objective forms of evaluation in an experiment in which participants viewed images of tended plant communities containing different color combinations. Our goal was to explore the effects of color combinations among tended plant communities on relaxation in humans by examining the effects of individual factors. We found that in terms of personal factors, gender modulated the recorded brain signals, reflecting differences in physiological and psychological states. Furthermore, tended plant communities with specific color combinations had different effects on human α waves and subjective evaluation data.

Gender has been reported to be an important factor in brain activity experiments (Allen et al. 2003; Joshi et al. 2020; Kranz et al. 2020). The current results revealed differences in α wave activity and subjective evaluation scores between men and women when viewing the experimental stimuli. Specifically, viewing images of foliage with different color combinations appeared to induce stronger feelings of relaxation in women compared with men. A previous study by Wang et al. (2021) yielded similar results when college office workers observed multiple bamboo landscapes, and women exhibited stronger α wave activity compared with men when viewing bamboo landscapes with two or more color combinations. This result is consistent with the responses of office workers to various plant colors, as reported by Li et al. (2013). When women viewed plants with different colors in an office, they reported feeling calm and happy, whereas the same images made men feel excited and nervous. Dupont et al. (2014) and Emery and Webster (2019) examined participants' visual evaluations of landscapes, confirming that women evaluated colors as being more beautiful compared with men. Tarashkar et al. (2020) also reported that female viewers had more positive psychological experiences, stronger behavioral characteristics, and greater landscape needs when appreciating garden landscapes, and that the emotional effects of landscape environments

were more obvious in female visitors. In a study of the effects of plant color, Elsadek (2014) reported that cerebral blood flow appeared to diminish in the feeling function areas when men viewed green plants. In contrast, in women, cerebral blood flow was less in brain areas related to judgment, motor control, visual processing and feeling function (Elsadek 2014). Besides, women exhibited more eye movement fixation when viewing green plants compared with men (Elsadek 2014). Taken together, these previous results could potentially provide a reasonable explanation for the current finding that women exhibited more relaxation than men after viewing images of plants. Considering color combinations intended plant communities from the perspective of gender may be useful for increasing the inclusiveness of landscape environments and providing a reference for human-centered design.

We confirmed that there was a correlation between our subjective evaluation and objective EEG data. This finding is consistent with previous research. Li et al. (2013) used a questionnaire survey and biofeedback methods (physiological measurements such as systolic pressure, diastolic pressure, and heart rate) to explore the impact of plant color on humans. The results revealed that the subjective questionnaire data were closely related to the objective data, and that both types of data reflected participants' physical and mental state. The studies described above indicate that human psychological and physical responses to the external environment (whether via visual or physical perception) are convergent. Our study revealed a low level of consistency between subjective evaluation and α wave power. This may have occurred because subjective emotions, such as those captured by a questionnaire, appear after physiological reactions. In addition, because of the strong sensitivity of EEG signals, some slight responses of the cerebral cortex cannot be reflected in the subjective evaluation.

Plant color factors

Plant communities containing one color

Among the plant community images containing only one color, 100% green plant communities and 100% yellow plant communities induced better relaxation effects than 100% red plant communities on the human body. Furthermore, the relaxation effect of green plant communities was slightly stronger than that of yellow plant communities, and 100% red plant communities had the smallest relaxation effect. This finding regarding the positive effects of green and yellow plants on the human body is consistent with previous research (Li 2013; Jang et al. 2019). Yellow hues were reported to be systematically associated with joy, whereas yellow-green hues were reported to be associated with

relaxation (Jonauskaite et al. 2018). Using a psychological questionnaire regarding emotional words, Jang et al. (2019) found that green plants produced "calm" and "comfortable" feelings, whereas red plants produced "uneasy" and "intense" feelings. Besides, an earlier study by Jang et al. (2014) reported that higher α wave power when viewing yellow flowers compared with red improved negative emotions and made people happier. Kexiu et al. (2021) found that watching green plants reduced Oxy-Hub in the brain, indicating a relaxed mood. Lohr and Pearson-Mims (2000), Shibata and Suzuki (2001), and Jang et al. (2014) found that when participants observed a green natural environment and green plants, α wave power significantly increased, reflecting enhanced relaxation. Mohamed et al. (2013) monitored blood flow in the right prefrontal cortex and reported that viewing green plants caused subjects to feel blessed, happy, and relaxed. Li (2013) reported that yellow leaf autumn landscapes aided relaxation and reduced anxiety more than red and red-yellow mixed color autumn landscapes. Fan and Niu (2014) reported that the presence of red plants significantly reduced α wave power. Therefore, landscapes with higher proportions of green and yellow plants and fewer red plants appear to have stronger relaxation effects.

Plant communities with two and three colors

Few previous studies have investigated the effects of tended plant communities with combinations of two or three colors, particularly in terms of the proportional and locational relationships of each color. To date, only the scenic beauty estimation method has been used as a summary of the overall effects of plant landscapes (Franco et al. 2003; Ribe 2009; Frank et al. 2013; Schirpke et al. 2013). That is, the use of a single color in large areas of a plant community may cause the scene to appear less vibrant, making the addition of other colors advantageous (Song and Che 2011). Zhuang et al. (2021) also reported that different proportions of cold and warm colors in plants can have different emotional effects, and that increasing the proportion of cold colors can benefit emotional health. On the basis of previous studies, we used EEG and subjective evaluation scores as objective measures of the effects of combinations of two or three plant colors on human physiology and psychology. Our findings also included information about color ratio and color position relationships.

Overall, the current findings demonstrated that relaxation effects were stronger when college students viewed images of plant communities containing two and three plant colors compared with monochromatic plant communities. These results are similar to the findings of Hoyle et al. (2018), who reported that meadow flowers with a high level of color diversity were more conducive to human perceptual recovery. Specifically, in plant communities with two colors and

a 55% + 45% color ratio, combinations of green + yellow and green + red induced stronger relaxation effects than the combination of yellow + red. This finding is consistent with the results obtained by Wang et al. (2018), who used physiological measures such as heart rate and blood pressure to examine the impact of plant color on the physical and mental health of college students. The combination of green and yellow plants was found to be the best for landscapes, followed by the combination of green and red plants. A study by Mohamed et al. (2017) reported that yellow + green plants can cause a significant reduction in blood oxyhemoglobin concentration in humans and produced a more relaxed and calm psychological feeling compared with red. This provides a reasonable explanation for the current findings. Previous articles by Kuller et al. (2009) and Elsadek (2014) reported that viewing the color red induces a state of arousal in the human brain and activates the motor areas. These previous findings may explain the weakening of relaxation effects as the amount of red in the visual scene increased in the current study.

However, different color positions and proportions may affect the degree of relaxation induced by viewing images of different plant communities. Thorpert (2019) discussed the effects of viewing distance on color perception and the effect of color contrast on visitors' experiences using color perception and environmental assessment methods. This previous study has some similarities with the current study, in which we examined the proportions and locations of plant communities, although we also measured and analyzed the physiological data of the participants.

Among plant communities with three colors, the relaxation effect was strongest when the color proportion of the plant community was 55% + 25% + 20% and the block position of each color was symmetrical and balanced. This finding is consistent with the finding of Lin and Li (2007) that in complex, changeable, and scattered environments, the application of simple colors and textures can produce a sense of unity in a space. Furthermore, when the proportion of green + yellow and green + red plants in plant communities with three colors exceeded 85%, the relaxation effect was strongest. A previous study reported that yellow-green hues were associated with relaxation and a feeling of joy (Jonauskaite et al. 2018). In one previous study, when subjects were exposed to groups of real green and red plants, the presence of green plants increased internal concentration more than the presence of red plants (Jang et al. 2019). Finally, the worst color ratio for relaxation was more than 85% yellow + red plants. A previous study suggested that exposure to warm colors with high visibility may lead to an acceleration of blood flow, increase in blood pressure, and acceleration of pulse, resulting in feelings of irritability and nervousness (Brambilla et al. 2020). In the current study, when the bottom shrub was yellow, the proportion of dark yellow was large, and α wave power was low after matching with the upper red shrub. Therefore, it may be helpful to consider both the proportional relationship among colors and the balanced distribution of colors in plant communities with three colors.

Although we used subjective evaluation combined with a physiological measurement to improve the accuracy of our data, the current study still involved several limitations. First, the subjects in this experiment were undergraduates and postgraduates aged between 18 and 27. Although related studies have reported that data obtained from college students in visual stimulation experiments were representative (Kaplan and Herbert 1987), the current results may not be fully generalizable to the general public. Second, the sample size in the current study was relatively small, comprising 40 participants. Further studies with larger samples are needed. Third, this experiment used stimuli depicting visual scenes from one particular climate, in which the recorded plant color types were relatively monotonous. Fourth, Photoshop software was used for image processing and color recognition in this study; MATLAB (Minervini et al. 2014) and Python (Chen et al. 2021a, b) could be used in future studies for accurate identification of environmental features. Fifth, additional research will be needed to fully explore the effects of color proportion and position gradient. Non-human animals are an important part of the ecosystem, and have different visual perception abilities and needs compared with those of humans (Athira et al. 2019). Future research on the effects of plant color on other species should also be conducted.

Conclusion

This study used plant community color combinations as a research object, and examined the effects of different color quantities, proportions, and positions on human physiology and psychology. We found that specific plant community color configurations had unique effects on relaxation.

The current findings indicated that women's EEG activity tended to indicate greater relaxation compared with that of men after viewing plant images. Different color combinations in the tended plant communities have different effects on observers' physiology and psychology. Thus, optimal color combinations may be useful for facilitating the physical and mental health of the public. In the future practice of plant community environment design, rich plant colors should be considered. Plant communities with two or three different colors were rated more positively than those with one color, and produced a stronger physiological response. Among plant communities with three colors, the relaxation effect was strongest when the color ratio was 55% + 25% + 20%, with green and yellow having the largest

proportion, and the color positions being evenly distributed. And, attention should be paid to the even distribution of the color proportions of multi-layer plant communities. In situations with a small number of plant colors, it may be beneficial to choose green or yellow plants, to provide people with more comfortable and relaxed environmental experiences. For example, the 55% + 45% color proportion with green + yellow and green + red combinations induced stronger relaxation effects compared with the yellow + red combination. The current study contributes to inform approaches for optimizing the role of plant color in garden spaces from both plant-focused and human-focused perspectives, and maximizing the health-promoting functions of tended plant communities.

References

Abdi B, Hami A, Zarehaghi D (2020) Impact of small-scale tree planting patterns on outdoor cooling and thermal comfort. Sustain Cities Soc 56:102085. https://doi.org/10.1016/j.scs.2020.102085

Allen JS, Damasio H, Grabowski TJ, Bruss J, Zhang W (2003) Sexual dimorphism and asymmetries in the gray–white composition of the human cerebrum. Neuroimage 18:880–894. https://doi.org/10.1016/S1053-8119(03)00034-X

Athira K, Sooraj NP, Jaishanker R, Saroj Kumar V, Sajeev CR, Pillai MS, Govind A, Ramarao N, Dadhwal VK (2019) Chromatic exclusivity hypothesis and the physical basis of floral color. Ecol Inform 49:40–44. https://doi.org/10.1016/j.ecoinf.2018.11.006

Atkinson J, Campos D (2016) Improving BCI-based emotion recognition by combining EEG feature selection and kernel classifiers. Expert Syst Appl 47:35–41. https://doi.org/10.1016/j.eswa.2015.10.049

Barone MJ (2005) The interactive effects of mood and involvement on brand extension evaluations. J Consum Psychol 15:263–270. https://doi.org/10.1207/s15327663jcp1503_11

Bazanova OM, Vernon D (2014) Interpreting EEG alpha activity. Neurosci Biobehav Rev 44:94–110. https://doi.org/10.1016/j.ctcp.2013.03.003

Behe B, Nelson R, Barton S, Hall C, Safley CD, Turner S (1999) Consumer preferences for geranium flower color, leaf variegation and price. HortScience 34:740–742. https://doi.org/10.21273/HORTSCI.32.3.510C

Berto R (2007) Assessing the restorative value of the environment: a study on the elderly in comparison with young adults and adolescents. Int J Psychol 42:331–341. https://doi.org/10.1080/00207590601000590

Brambilla A, Hu WY, Samangouei R, Cadorin R, Davis W (2020) How correlated color temperature manipulates human thermal perception and comfort. Build Environ 177:106929. https://doi.org/10.1016/j.buildenv.2020.106929

Chang CY (2004) Psychophysiological responses to different landscape settings and a comparison of cultural differences. Acta Hortic 639:57–65. https://doi.org/10.17660/ActaHortic.2004.639.6

Chang CY, Chen PK (2005) Human response to window views and indoor plants in the workplace. HortScience 40:1354–1359. https://doi.org/10.21273/HORTSCI.40.5.1354

Chen T, Pan H, Lu M, Hang J, Lam CKC, Yuan C, Pearlmutter D (2021a) Effects of tree plantings and aspect ratios on pedestrian visual and thermal comfort using scaled outdoor experiments. Sci Total Environ 801:149527. https://doi.org/10.1016/j.scitotenv.2021.149527

Chen Y, Chen L, Li Y (2021b) Recognition algorithm of street landscape in cold cities with high difference features based on improved neural network. Ecol Inform 66:101395. https://doi.org/10.1016/j.ecoinf.2021.101395

Dupont L, Antrop M, Van Eetvelde V (2014) Eye-tracking analysis in landscape perception research: influence of photograph properties and landscape characteristics. Landsc Res 39:417–432. https://doi.org/10.1080/01426397.2013.773966

Dupont L, Antrop M, Van Eetvelde V (2015) Does landscape related expertise influence the visual perception of landscape photographs? Implications for participatory landscape planning and management. Landsc Urban Plan 141:68–77. https://doi.org/10.1016/j.landurbplan.2015.05.003

Dupont L, Ooms K, Antrop M, Van Eetvelde V (2016) Comparing saliency maps and eye-tracking focus maps: the potential use in visual impact assessment based on landscape photographs. Landsc Urban Plan 148:17–26. https://doi.org/10.1016/j.landurbplan.2015.12.007

Elsadek M (2014) People's psycho-physiological responses to plant scape colors stimuli: a pilot study. Int J Psychophysiol 4:70–78. https://doi.org/10.5923/j.ijpbs.20140402.02

Emery KJ, Webster MA (2019) Individual differences and their implications for color perception. Curr Opin Behav Sci 30:28–33. https://doi.org/10.1016/j.cobeha.2019.05.002

Fan YH, Niu X (2014) Research on the physiological effects of plants and flowers on office workers in coal mining areas. Coal 23(8):90–92

Franco D, Franco D, Mannino I, Zanetto J (2003) The impact of agroforestry networks on scenic beauty estimation: the role of a landscape ecological network on a socio-cultural process. Landsc Urban Plan 62:119–138. https://doi.org/10.1016/s0169-2046(02)00127-5

Frank S, Furst C, Koschke L, Witt A, Makeschin F (2013) Assessment of landscape aesthetics—validation of a landscape metrics-based assessment by visual estimation of the scenic beauty. Ecol Indic 32:222–231. https://doi.org/10.1016/j.ecolind.2013.03.026

Galadí JA, Torres JJ, Marro J (2020) Emergence and interpretation of oscillatory behaviour similar to brain waves and rhythms. Commun Nonlinear Sci Numer Simul 83:105093. https://doi.org/10.1016/j.cnsns.2019.105093

Gao XP, Xin JH (2006) Investigation of human's emotional responses on colors. Color Res Appl 31:411–417. https://doi.org/10.1002/col.20246

Heerwagen JH, Orians GH (1993) Affect and aesthetics: humans, habitats and aesthetics. The biophilia hypothesis. Island Press, Washington DC, pp 138–172

Hoyle H, Norton B, Dunnett N, Richards JP, Russell JM, Warren P (2018) Plant species or flower colour diversity? Identifying the drivers of public and invertebrate response to designed annual meadows. Landsc Urban Plan 180:103–113. https://doi.org/10.1016/j.landurbplan.2018.08.017

Hůla M, Flegr J (2016) What flowers do we like? The influence of shape and color on the rating of flower beauty. PeerJ 4:e2106. https://doi.org/10.7717/peerj.2106

Hull RB, Stewart WP (1992) Validity of photo-based scenic beauty judgments. J Environ Psychol 12:101–114. https://doi.org/10.1016/S0272-4944(05)80063-5

Jacobs KW, Hustmyer FE (1974) Effects of four psychological primary colors on GSR, heart rate and respiration rate. Percept Mot Skills 38:763–766. https://doi.org/10.2466/pms.1974.38.3.763

Jang HS, Kim J, Kim KS, Pak CH (2014) Human brain activity and emotional responses to plant color stimuli. Color Res Appl 39:307–316. https://doi.org/10.1002/col.21788

Jang HS, Gim GM, Jeong SJ, Kim JS (2019) Changes in physiological and psychological conditions of humans to color stimuli of plants. J People Plants Environ 2:127–143

Jap BT, Lal S, Fischer P, Bekiaris E (2009) Using EEG spectral components to assess algorithms for detecting fatigue. Expert Syst Appl 36:2352–2359. https://doi.org/10.1016/j.eswa.2007.12.043

Jonauskaite D, Althaus B, Dael N, Dan-Glauser E, Mohr C (2018) What color do you feel? Color choices are driven by mood. Color Res Appl 44:272–284. https://doi.org/10.1002/col.22327

Joshi PD, Wakslak CJ, Appel G, Huang L (2020) Gender differences in communicative abstraction. J Pers Soc Psychol 118:417–435. https://doi.org/10.1037/pspa0000177

Kamei T, Toriumi Y, Kimura H, Ohno S, Kumano H, Kimura K (2000) Decrease in serum cortisol during yoga exercise is correlated with alpha wave activation. Percept Mot Skills 90:1027–1032. https://doi.org/10.2466/pms.2000.90.3.1027

Kaplan R, Herbert EJ (1987) Culture and sub-culture comparisons in preferences for natural setting. Landsc Urban Plan 14:281–293. https://doi.org/10.1016/0169-2046(87)90040-5

Kaufman AJ, Lohr VI (2004) Dose plant color affect emotional and physiological responses to landscapes. Acta Hortic 639:229–233. https://doi.org/10.17660/ActaHortic.2004.639.29

Kexiu L, Elsadek M, Liu B, Fujii E (2021) Foliage colors improve relaxation and emotional status of university students from different countries. Heliyon 7:e06131. https://doi.org/10.1016/j.heliyon.2021.e06131

Kiloh LG (1982) The brain and psychiatry. Aust N Z J Psychiatry 16:34–42. https://doi.org/10.3109/00048678209159468

Kranz GS, Zhang BBB, Handschuh P, Ritter V, Lanzenberger R (2020) Gender-affirming hormone treatment—a unique approach to study the effects of sex hormones on brain structure and function. Cortex 129:68–79. https://doi.org/10.1016/j.cortex.2020.04.005

Kreibig SD (2010) Autonomic nervous system activity in emotion: a review. Biol Psychol 84:394–421. https://doi.org/10.1016/j.biopsycho.2010.03.010

Kuller R, Mikellides B, Janssens J (2009) Color, arousal and performance—a comparison of three experiments. Color Res Appl 34:141–152. https://doi.org/10.1002/col.20476

Lakkaraju VR, Zhou X, Apple ME, Cunningham A, Dobeck LM, Gullickson K, Spangler LH (2010) Studying the vegetation response to simulated leakage of sequestered CO_2 using spectral vegetation indices. Ecol Inform 5:379–389. https://doi.org/10.1016/j.ecoinf.2010.05.002

Lee JS, Kim CS, Yim OY, Lee DH (2002) Measurement of area effect by the color panel size. In: Proceedings of SPIE. 4421, 9th Congress of the International Colour Association, pp 158−161. https://doi.org/10.1117/12.464537. Accessed 6 June 2002

Lev-Yadun S, Holopainen JK (2009) Why red-dominated autumn leaves in America and yellow-dominated autumn leaves in Northern Europe? New Phytol 183:506–512. https://doi.org/10.1111/j.1469-8137.2009.02904.x

Li Q (2013) A novel Likert scale based on fuzzy sets theory. Expert Syst Appl 40:1609–1618. https://doi.org/10.1016/j.eswa.2012.09.015

Li X, Hu XZ, Lu YM, Pan HT (2013) The influence of plant landscape colors on the visual psychology of college students. Chin Landsc Archit 29(7):93–97 (**in Chinese**)

Lin J, Li Y (2007) The influence of visual characteristics on the creation of plant landscape space. J Beijing for Univ (soc Sci) 1:46 (**in Chinese**)

Liu J, Kang J, Behm H, Luo T (2014) Effects of landscape on soundscape perception: soundwalks in city parks. Landsc Urban Plan 123:30–40. https://doi.org/10.1016/j.landurbplan.2013.12.003

Lohr VI, Pearson-Mims CH (2000) Physical discomfort may be reduced in the presence of interior plants. HortTechnology 10:53–58. https://doi.org/10.21273/HORTTECH.10.1.53

Lutz A, Slagter HA, Dunne JD, Davidson RJ (2008) Cognitive-emotional interactions: attention regulation and monitoring in meditation. Trends Cogn Sci 12:163–169. https://doi.org/10.1016/j.tics.2008.01.005

Minervini M, Abdelsamea MM, Tsaftaris SA (2014) Image-based plant phenotyping with incremental learning and active contours. Ecol Inform 23:35–48. https://doi.org/10.1016/j.ecoinf.2013.07.004

Mohamed E, Sato S, Eijiro F, Eid K, Eman M, Yehia AE (2013) Human emotional and psycho-physiological responses to plant color stimuli. J Food Agric Environ 11(3–4):1584–1591

Mohamed E, Minkai S, Eijiro F, Eid K, Eman M, Yehia AE (2017) Psycho-physiological responses to plant variegation as measured through eye movement, self-reported emotion and cerebral activity. Indoor Built Environ 26:758–770. https://doi.org/10.1177/1420326X16638711

Narimani N, Karimi A, Brown RD (2022) Effects of street orientation and tree species thermal comfort within urban canyons in a hot, dry climate. Ecol Inform 69:101671. https://doi.org/10.1016/j.ecoinf.2022.101671

Peen J, Schoevers RA, Beekman AT, Dekker J (2010) The current status of urban-rural differences in psychiatric disorders. Acta Psychiatr Scand 121:84–93. https://doi.org/10.1111/j.1600-0447.2009.01438.x

Ren XX, Kang J (2015) Interactions between landscape elements and tranquility evaluation based on eye tracking experiments. J Acoust Soc Am 138:3019–3022. https://doi.org/10.1121/1.4934955

Ribe RG (2009) In-stand scenic beauty of variable retention harvests and mature forests in the US Pacific Northwest: the effects of basal area, density, retention pattern and down wood. J Environ Manag 91:245–260. https://doi.org/10.1016/j.jenvman.2009.08.014

Robins RK, Hollands MA (2017) The effects of constraining vision and eye movements on whole-body coordination during standing turns. Exp Brain Res 235:3593–3603. https://doi.org/10.1007/s00221-017-5079-0

Saito M (1996) A comparative study of color preferences in Japan, China and Indonesia, with emphasis on the preference for white. Percept Mot Skills 83:115–128. https://doi.org/10.2466/pms.1996.83.1.115

Schirpke U, Tasser E, Tappeiner U (2013) Predicting scenic beauty of mountain regions. Landsc Urban Plan 111:1–12. https://doi.org/10.1016/j.landurbplan.2012.11.010

Serra J, Manav B, Gouaich Y (2021) Assessing architectural color preference after Le Corbusier's 1931 Salubra keyboards: a cross cultural analysis. Front Archit Res 10:502–515. https://doi.org/10.1016/j.foar.2021.03.002

Shi GY, Zhou Y, Sang YQ, Huang H, Zhang JS, Meng P, Cai LL (2021) Modeling the response of negative air ions to environmental factors using multiple linear regression and random forest. Ecol Inform 66:101464. https://doi.org/10.1016/j.ecoinf.2021.101464

Shibata S, Suzuki N (2001) Effects of indoor foliage plants on subjects' recovery from mental fatigue. N Am J Psychol 3(3):385–396

Shibata S, Suzuki N (2004) Effects of an indoor plant on creative task performance and mood. Scand J Psychol 45:373–381. https://doi.org/10.1111/j.1467-9450.2004.00419.x

Sinkkonen A (2006) Sexual reproduction advances autumn leaf colours in mountain birch. J Evol Biol 19:1722–1724. https://doi.org/10.1111/j.1420-9101.2005.00991.x

Song YN, Che SQ (2011) Evaluation of the beauty degree of typical plant communities in Shanghai city parks. J Shanghai Jiaotong Univ (agric Sci) 29(2):16–24 (**in Chinese**)

Stevens CE, Zabelina DL (2019) Creativity comes in waves: an EEG-focused exploration of the creative brain. Curr Opin Behav Sci 27:154–162. https://doi.org/10.1016/j.cobeha.2019.02.003

Stinson B, Arthur D (2013) A novel EEG for alpha brain state training, neurobiofeedback and behavior change. Complement Ther Clin Pract 19:114–118. https://doi.org/10.1016/j.ctcp.2013.03.003

Tarashkar M, Hami A, Namin FE (2020) The effects of parks' landscape characteristics on women's perceptual preferences in semi-arid environments. J Arid Environ 174:104080. https://doi.org/10.1016/j.jaridenv.2019.104080

Thorpert P (2019) Green is not just green. Human colour perception in urbangreen contexts. PhD thesis Alnarp: Department of Landscape Architecture, Planning and Management, Swedish University of Agricultural Sciences

Thorpert P, Englund J, Nielsen AB (2018) The impact of the primary colours yellow, red and blue on the perception of greenery. Landsc Res 44:1–11. https://doi.org/10.1080/01426397.2017.1413177

Tomitaka M, Uchihara S, Goto A, Sasaki T (2021) Species richness and flower color diversity determine aesthetic preferences of natural-park and urban-park visitors for plant communities. Environ Dev Sustain 11:100130. https://doi.org/10.1016/j.indic.2021.100130

Tucker DM, Hartry-Speiser A, McDougal L, Luu P, De Grandpre D (1999) Mood and spatial memory: emotion and right hemisphere contribution to spatial cognition. Biol Psychol 50:103–125. https://doi.org/10.1016/s0301-0511(99)00005-8

Ulrich RS (1984) View through a window may influence recovery from surgery. Science 224:420–421. https://doi.org/10.1126/science.6143402

Ulrich RS, Simons RF, Losito BD, Fiorito E, Miles MA, Zelson M (1991) Stress recovery during exposure to natural and urban environments. J Environ Psychol 11:201–230. https://doi.org/10.1016/S0272-4944(05)80184-7

Wang JH (2019) Language cognitive technology research. China Renmin University Press, Beijing, pp 96–138

Wang DN, Zhang H, Arens E, Huizenga C (2007) Observations of upper-extremity skin temperature and corresponding overall-body thermal sensations and comfort. Build Environ 42:3933–3943. https://doi.org/10.1016/j.buildenv.2006.06.035

Wang ZMQ, Li KK, Dou L, Xu Z, Liu JJ (2018) The recovery effect of plant color on the negative emotions of college students. J Northwest for Univ 33(3):290–296

Wang Z, Li MY, Zhang XH, Song LY (2020) Modeling the scenic beauty of autumnal tree color at the landscape scale: a case study of Purple Mountain, Nanjing, China. Urban for Urban Green 47:126526. https://doi.org/10.1016/j.ufug.2019.126526

Wang YQ, Qu H, Bai T, Chen QB, Li X, Luo ZH, Lv BY (2021) Effects of variations in color and organ of color expression in urban ornamental bamboo landscapes on the physiological and psychological responses of college students. Int J Environ Res Public Health 18:1151. https://doi.org/10.3390/ijerph18031151

Yao Y, Zhu XD, Xu YB, Yang HY, Wu X, Li YF, Zhang YF (2012) Assessing the visual quality of green landscaping in rural residential areas: the case of Changzhou, China. Environ Monit Assess 184:951–967. https://doi.org/10.1007/s10661-011-2012-z

Yao X, Ji B, Li M, Men Y, Jin X (2020) Research on the impact of road landscape color on the driving fatigue of drivers. IOP Conf Ser: Earth Environ Sci 440:042044. https://doi.org/10.1088/1755-1315/440/4/042044

Zhao JW, Xu WY, Ye L (2018) Effects of auditory-visual combinations on perceived restorative potential of urban green space. Appl Acoust 141:169–177. https://doi.org/10.1016/j.apacoust.2018.07.001

Zhuang J, Qiao L, Zhang X, Su Y, Xia Y (2021) Effects of visual attributes of flower borders in urban vegetation landscapes on aesthetic preference and emotional perception. Int J Environ Res Public Health 18:9318. https://doi.org/10.3390/ijerph18179318