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Brain Wave Changes in the Prefrontal Cortex When Exposed to Varying Plant Types as Visual Stimuli

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Abstract. **Visual stimuli from green plants have positive effects on mental health. This study aimed to compare human responses to varying plant types [live, artificial, two-dimensional (2D), and three-dimensional (3D) plant models] as visual stimuli. Thirty adults (age, 29.9 ± 11.5 years) viewed each plant form while an electroencephalography (EEG) measured their brain activity. Psychological responses were assessed using the semantic differential method (SDM). No significant differences were observed among visual stimuli; however, brain activity differences varied between male and female participants. Males who observed live and artificial plants had a higher relative alpha (RA) spectrum (RAS) and relative fast alpha (RFA) spectrum frequencies at Fp1 and Fp2 ($P < 0.05$ and $P < 0.01$ vs. $P < 0.05$ and $P < 0.01$, respectively), indicating greater emotional stability. Similarly, male participants who viewed 2D models had higher RA and RFA frequencies at Fp1 ($P < 0.01$, $P < 0.01$) and Fp2 ($P < 0.05$, $P < 0.01$). Male participants who observed 3D models exhibited higher RA, RSA, and RFA frequencies at Fp1 ($P < 0.01$). Live and artificial plants were deemed the most calming ($P < 0.01$). Both sexes found live plants to be the most pleasant (males: $P < 0.01$; females: $P < 0.05$) and natural (males: $P < 0.001$; females: $P < 0.01$). Overall, alpha wave differences were not significant among plant types, and live plants elicited a trend toward emotional stability. These findings suggest that 3D plant models can be as effective as real plants in psychophysiological applications, indicating their potential benefits for enhancing mental health in urban environments.**

Humans receive sensory information primarily through visual channels, which account for more than 70% of sensory input (Hutmacher 2019). The brain, which is crucial for cognition and behavior, generates electrical activity known as brain waves that reflect neurotransmitter transport across neurons (Kim et al. 2021). Key brain lobes (frontal, temporal, parietal, and occipital) play distinct roles; notably, the frontal lobe governs executive functions, reality perception, and emotional regulation (Duncan and Owen 2000). Compared with other lobes, it exhibits heightened activity in response to emotional changes (Sarno et al. 2016), making it pivotal in processing visual esthetic experiences that influence perceptions, mood, and stress levels.

Currently, the majority of the world population (individuals who live in urban areas) spend more than 80% of their time indoors (Yoo and Lee 2014). According to the International Telecommunication Union, the smartphone usage rate among adults has increased steadily from 93% in 2017 to 97% in 2022. The increased use of smartphones, computers, and other electronic devices has led to human disconnection with nature (Richardson et al. 2018) and increased levels of stress. Urban environmental stress significantly exacerbates fatigue and stress among urban dwellers, thus contributing to mental health deterioration (Triguero-Mas et al. 2017). Integrating nature into urban environments can help individuals cope with negative emotions and stressors (Reddon and Durante 2018). Consequently, to improve access to nature, the need for green spaces has increased (Lee 2007).

Horticultural therapy, a form of green care, is defined as the use of tailored horticultural activities conducted by professionals to enhance the mental and physical well-being of participants (Park et al. 2016). Horticultural therapy improves physical, psychological, social, cognitive, and behavioral health (Cipriani et al. 2017). Specifically, horticultural therapy enhances agricultural skills, self-esteem, confidence, quality of life, emotional stability, interpersonal relationships, and trust in others (Gonzalez et al. 2011). Horticultural activities enable modern individuals to easily interact with natural elements even within restricted urban environments (Park et al. 2016). Moreover, horticultural activities significantly improve cognitive health-related factors by enhancing brain-derived neurotrophic factor and platelet-derived growth factor levels, whereas visual and auditory stimuli derived from forests significantly decrease oxyhemoglobin concentrations in the prefrontal cortex and increase parasympathetic nervous system activity, thus promoting a comfortable and stable state in the elderly (Song et al. 2021).

The use of virtual nature environments to improve public health, especially for urban residents who spend increased time indoors, has gained considerable attention (Reddon and Durante 2018). Visual stimulation with plants decreases the concentration of oxyhemoglobin in the prefrontal cortex, thus stabilizing the prefrontal cortex (Oh et al. 2019). When viewing natural environments indoors, alpha and beta waves increase and blood pressure decreases; furthermore, plants provide comfort and a sense of being in nature (Chang and Chen 2005). Engaging in activities, such as viewing trees using immersive virtual reality, leads to better immersion experiences compared with those when viewing screens, as reported through immersion experience scales and nature relevance scales (Spangenberger et al. 2022). Tactile stimulation studies revealed that touching *Epipremnum aureum* leads to a significant decrease in the oxyhemoglobin concentration in the prefrontal cortex, thus promoting relaxed and tranquil responses, as observed through a semantic analysis (Koga and Iwasaki 2013).

Thus, plants provide diverse benefits and natural environments induce positive effects in humans. However, studies of the effects of exposure to different display forms of plants remain limited. Therefore, in this study, we aimed to determine the differences in visual stimuli according to plant types using self-

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Fig. 1. List of plant types used during the experiment. 3D = three dimensional.

report questionnaires, electroencephalography (EEG), and the semantic differential method (SDM).

Materials and Methods

Participants. Based on the assumption of a normally distributed population, as indicated by previous psychophysiological studies involving horticultural activities (Kim and Park 2020), 30 adults were recruited for the current study (n = 15 males and n = 15 females; age, 20–60 years). This number was chosen to balance the need for sufficient statistical power with the practical constraints of conducting detailed neurophysiological measurements using EEG. The recruitment process involved the posting of notices containing information about the study in schools and libraries near Gwangjin-gu, Seoul, between 22 Jan 2024 and 1 Feb 2024. The inclusion criteria were as follows: right-hand dominance (Tarkka and Hallett 1990) and no allergies to plants. The exclusion criteria included current illnesses (Choi et al. 2016) and visual impairments. Additionally, to minimize the influence of caffeine (Heckman et al. 2010), the participants were asked to abstain from food and drinks containing caffeine for at least 3 h before the experiment. Adults who were willing to participate were briefed about the purpose, procedures, and expected outcomes of the study. Those who voluntarily expressed their willingness to participate and signed informed consent forms were selected. This study was approved by the Institutional Review Board of Konkuk University (7001355-202310-HR-709).

Experimental environment. The experiment was conducted in a laboratory located at the Konkuk University campus. The interior space of the laboratory was set to 2.0 m × 2.0 m to create the workspace area according to the standards of the American National Standard Institute and the guidelines of the International Facility Management Association. The indoor environment was regulated based on the recommendations of the American Society of Heating, Refrigerating and Air-Conditioning Engineers (2009), with temperatures set between 23 and 26 °C, relative humidity maintained at 30% ± 10% (O-257; DRETEC Co., Ltd., Saitama, Japan), and illuminance levels less than 700 lx (ST-126; SINCON, Bucheon, Korea). Ivory-color blackout curtains were installed to block visual elements and create a sealed workspace. Chairs with adjustable angles and comfortable support were provided.

Experimental protocol. Before the experiment commenced, all participants were briefed to avoid unnecessary activities or conversations. They entered the experimental space, donned EEG caps, and rested in chairs to establish a baseline stable condition for 90 s. Subsequently, the participants observed four plant categories [live, artificial, two-dimensional (2D), three-dimensional (3D)] (Fig. 1) for 90 s each. The types of plants used in each category were as follows: the live plant was *Epipremnum aureum* (commonly known as Golden Pothos); the artificial plant was a plastic *Epipremnum aureum*; the 2D plant was a picture of *Epipremnum aureum*; and the 3D plant was a 3D graphic model of *Epipremnum aureum*. Immediately after each observation, the participants responded to self-report surveys (SDM). In summary, the experimental protocol consisted of 90 s of rest, 90 s of activity, and the survey; these were repeated until the participants completed all four planned activities (Fig. 2).

Measurements. The EEG measurement device (Quick-20; Cognionics, San Diego, CA, USA) used in this study was certified by both the European Committee and the Federal Communications Commission (Kim et al. 2020) and used advanced dry electrode technology, which minimized the need for conductive gel, reduced the preparation time, and enhanced participant comfort during prolonged EEG measurements. The EEG monitoring was conducted at frontal polar sites (Fp1, Fp2) following the international 10–20 electrode placement system (Jasper 1958; Klem et al. 1999), with a reference electrode positioned on the left earlobe (A1) (Fig. 3). Before data collection, impedance of each electrode was meticulously checked, and adjustments were made to ensure optimal comfort and contact with the scalp. Amplification of electrical signals from the scalp was achieved using dry electrodes to collect data during visual stimulation. The EEG signals were sampled at a high rate of 1 kHz, thus ensuring high temporal resolution to capture rapid changes in brain activity.

The SDM, developed by Osgood et al. (1957), evaluates subjective emotions using pairs of adjective words (Osgood et al. 1957). The SDM used in this study consisted of a 7-point scale with three items (unpleasant–pleasant, artificial–natural, tense–relax).

Data analysis. The EEG measurements were analyzed using Bioteck Analysis (version 1.0; CGX, San Diego, CA, USA). The data underwent bandpass filtering (0.5–100 Hz) using the built-in amplifier and brain mapping program (Bioteck Analysis Software; Daejeon, South Korea), and they were collected at a sampling rate of 1 kHz. The EEG signals were measured as complex waveforms that required classification of signals into frequency bands before analysis (Hwang and Nam 2023). Therefore, the collected EEG data were classified into the following three power spectra: relative alpha (RA), relative slow alpha (RSA), and relative fast alpha (RFA). The RA (8–13 Hz), RSA (8–11 Hz), and RFA (11–13 Hz) power spectra were analyzed based on power ratios in the 4- to 50-Hz and 8- to 13-Hz bands, indicating relaxation and stabilization (Klink et al. 2020). These parameters reflected the physiological state of the brain. A one-way analysis of variance and Duncan's post hoc test were used to examine the differences and rankings among the four treatment groups. Independent *t* tests were performed to investigate brain wave differences between the sexes. The statistical significance level for all analyses was set at $P < 0.05$. IBM SPSS Statistics 26.0 (IBM Inc., Armonk, NY, USA) statistical software was used for the analysis.

Results

Demographic information. This study included 30 participants (age, 20–60 years); the distribution of males and females was equal. Characteristics of the participants are presented in Table 1.

Physiological responses. No significant differences were observed in the RA frequencies at Fp1 (left prefrontal cortex) and Fp2 (right prefrontal cortex) ($P > 0.05$) among the four treatment groups (live, artificial, 2D model, and 3D model plants). Similarly, no significant differences were observed in the RSA frequencies at Fp1 and Fp2 or

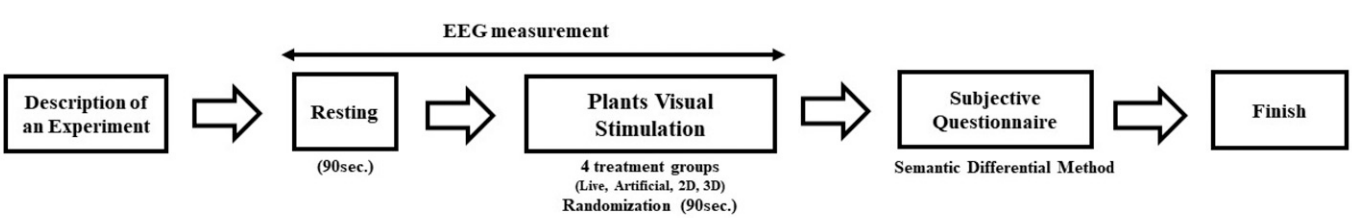

Fig. 2. Experiment protocol.

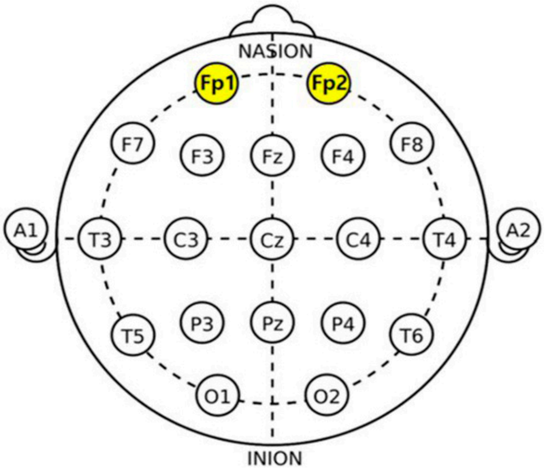

Fig. 3. Electrode locations of the international 10–20 system for electroencephalography (EEG).

Table 1. Demographic information of the study participants.

Variance	Male (n = 15)	Female (n = 15)	Total (N = 30)
	Mean ± *SD*		
Age	27.4 ± 7.4	32.4 ± 14.3	29.9 ± 11.5
Height (cm)[i]	173 ± 3.9	162.2 ± 5.8	167.7 ± 7.4
Weight (kg)[ii]	69.6 ± 10	56.5 ± 5.8	63.1 ± 10
Body mass index (kg/m^2)[iii]	23.2 ± 3.4	21.4 ± 1.9	22.4 ± 2.9[iv]

[i] Height was measured using an anthropometer (Ok7979; Samhwa, Seoul, South Korea) without shoes.
[ii] Weight was measured using a body fat analyzer (ioi 353; Jawon Medical, Gyeongsan-si, South Korea).
[iii] Body mass index was calculated using the following formula: [weight (kg)]/[height (cm^2)].
[iv] Within the normal range proposed by the World Health Organization.

in the RFA frequencies at Fp1 and Fp2 among the four treatment groups ($P > 0.05$) (Table 2).

No differences were found between Fp1 and Fp2 RA frequencies among the four treatment groups ($P > 0.05$). Similarly, there were no significant differences in RSA frequency changes between Fp1 and Fp2 or in RFA frequency changes between Fp1 and Fp2 ($P > 0.05$) (Table 3).

Compared with females, males exhibited significantly higher RA frequencies at Fp1 and Fp2 (both $P < 0.05$) when observing live plants. In addition, compared with females, males exhibited significantly higher RA frequencies at Fp1 when observing artificial plants ($P < 0.05$). Similarly, when males observed 2D models, they exhibited significantly higher RA frequencies at Fp1 ($P < 0.01$) and Fp2 than those of females ($P < 0.05$). Additionally, when males observed 3D models, they showed significantly higher RA frequencies at Fp1 than those of females ($P < 0.01$).

Compared with males, females exhibited significantly higher RSA frequencies at Fp1 ($P < 0.05$) when observing live plants; furthermore, males exhibited significantly higher RSA frequencies at Fp2 ($P < 0.05$) than those of females. Additionally, when males observed 3D models, they showed significantly higher RSA frequencies at Fp1 than those of females ($P < 0.01$).

Compared with females, males exhibited significantly higher RFA frequencies at Fp1 ($P < 0.01$) and Fp2 ($P < 0.05$) when observing live plants. Similarly, when observing artificial plants, males showed significantly higher RFA frequencies at Fp1 and Fp2 than those of females ($P < 0.05$). When observing 2D models, males exhibited significantly higher RFA frequencies at Fp1 than those of females; furthermore, females exhibited significantly higher RFA frequencies at Fp2 than those of males ($P < 0.01$). When observing 3D models, males exhibited significantly higher RFA frequencies at Fp1 than those of females ($P < 0.01$) (Table 4).

Semantic differential method. Participants responded that live plants were the most pleasant ($P < 0.001$) and the most natural ($P < 0.001$) to observe. When observing live and artificial plants, participants responded that they felt the most relaxed ($P < 0.01$) (Table 5).

Males ($P < 0.01$) and females ($P < 0.05$) rated live plants as the most pleasant among the four treatment groups. No significant differences in the pleasantness category across the four treatment groups were observed between sexes ($P > 0.05$). Similarly, males ($P < 0.01$) and females ($P < 0.001$) rated live plants as the most natural among the four treatment groups, with no significant differences in the naturalness category across the four treatment groups between sexes ($P > 0.05$). When observing live plants, males reported feeling the most relaxed ($P < 0.05$). However, females reported feeling more relaxed when observing artificial plants ($P > 0.01$) (Table 6).

Discussion

This study measured and compared the psychophysiological and psychological responses to visual stimuli using four different types of plants. When observing the plants in different forms (live, artificial, 2D, and 3D), no significant differences were observed in the RA, RSA, and RFA frequencies at Fp1 and Fp2. These results confirm the findings of previous research studies that reported that similar positive emotions and feelings of restoration occur when viewing natural and virtual natural stimuli (Browning et al. 2019). In addition, realistically designed 3D images of natural landscapes and real landscapes conferred comparable results (Juliantino et al. 2023), and no significant differences in brain wave responses with live, artificial, and 2D stimuli were observed (Oh et al. 2019). However, the short duration of plant observation during this

Table 2. Comparison of responses based on plant types.

Visual stimuli	RA[i] Fp1	RA[i] Fp2	RSA[ii] Fp1	RSA[ii] Fp2	RFA[iii] Fp1	RFA[iii] Fp2
	Mean ± *SD*					
Real plant	0.168 ± 0.03	0.164 ± 0.035	0.116 ± 0.027	0.113 ± 0.024	0.051 ± 0.014	0.051 ± 0.013
Artificial plant	0.17 ± 0.042	0.166 ± 0.039	0.118 ± 0.03	0.115 ± 0.029	0.052 ± 0.015	0.051 ± 0.013
Picture of a plant	0.169 ± 0.041	0.166 ± 0.035	0.117 ± 0.029	0.115 ± 0.025	0.052 ± 0.014	0.05 ± 0.012
Plant 3D model	0.167 ± 0.043	0.165 ± 0.036	0.116 ± 0.031	0.116 ± 0.027	0.05 ± 0.014	0.049 ± 0.011
F	0.043	0.019	0.022	0.077	0.117	0.108
P value	0.998[NS]	0.996[NS]	0.996[NS]	0.972[NS]	0.950[NS]	0.955[NS]

[i] RA refers to the relative alpha power spectrum: (8–13 Hz)/(4–50 Hz).
[ii] RSA refers to the relative slow alpha power spectrum: (8–11 Hz)/(4–50 Hz).
[iii] RFA refers to the relative fast alpha power spectrum: (11–13 Hz)/(4–50 Hz).
3D = three-dimensional; NS = nonsignificant according to the one-way analysis of variance.

Table 3. Comparison of left and right prefrontal cortex responses to different plant types.

Spectrum	Visual stimuli	Fp1	Fp2	t	P value
RA[i]	Real plant	0.168 ± 0.03	0.164 ± 0.035	1.210	0.236^{NS}
	Artificial plant	0.17 ± 0.042	0.166 ± 0.039	1.327	0.195^{NS}
	Picture of a plant	0.169 ± 0.041	0.166 ± 0.035	1.187	0.245^{NS}
	Plant 3D model	0.167 ± 0.043	0.165 ± 0.036	0.255	0.800^{NS}
RSA[ii]	Real plant	0.116 ± 0.027	0.113 ± 0.024	1.262	0.217^{NS}
	Artificial plant	0.118 ± 0.03	0.115 ± 0.029	0.980	0.335^{NS}
	Picture of a plant	0.117 ± 0.029	0.115 ± 0.025	0.992	0.329^{NS}
	Plant 3D model	0.116 ± 0.031	0.116 ± 0.027	0.073	0.942^{NS}
RFA[iii]	Real plant	0.051 ± 0.014	0.051 ± 0.013	0.876	0.388^{NS}
	Artificial plant	0.052 ± 0.015	0.051 ± 0.013	1.895	0.068^{NS}
	Picture of a plant	0.052 ± 0.014	0.05 ± 0.012	1.379	0.178^{NS}
	Plant 3D model	0.05 ± 0.014	0.049 ± 0.011	0.678	0.503^{NS}

[i] RA refers to the relative alpha power spectrum: (8–13 Hz)/(4–50 Hz).
[ii] RSA refers to the relative slow alpha power spectrum: (8–11 Hz)/(4–50 Hz).
[iii] RFA refers to the relative fast alpha power spectrum: (11–13 Hz)/(4–50 Hz).
3D = three-dimensional; NS = nonsignificant according to the paired t test.

study may explain the lack of differences among the four treatment groups (Jeong and Park 2021; Oh et al. 2019).

Brodmann area 10, a subdivision of the prefrontal cortex known as the anterior prefrontal cortex, primarily regulates executive functions, such as planning, decision-making, and problem-solving, as well as cognitive control, working memory, and the formulation of plans. Typically, the left hemisphere controls the right side of the body, language, classification abilities, and typical behaviors, whereas the right hemisphere specializes in responding to emergencies, spatial organization, face recognition, and emotion processing (MacNeilage et al. 2009). Positron emission tomography studies have shown that cortical activation in the brain increases as task complexity increases (Chiaravalloti et al. 2019). The frontal lobe processes information received from various brain regions through interconnected networks, which are responsible for executing responses, retrieving memories, and assessing emotions (Miller and Cohen 2001). However, the results of the present study showed no difference between the left and right prefrontal cortex, indicating a similar level of emotional stability. This suggested similar psychophysiological stability across participants during plant observation. Psychophysiological stability in this context refers to the consistent brain activity patterns and reduced variability in emotional responses, thus contributing to reduced stress and enhanced mental well-being.

When observing live plants, the RA and RFA frequencies in Fp1 and Fp2 in males were significantly higher than those in females. Similarly, while observing artificial plants, RA and RFA frequencies in males (in Fp1 and in Fp1 and Fp2, respectively) were significantly higher than those in females. These findings are supported by the findings of studies that measured cerebral blood flow between sexes using positron emission tomography, thus indicating higher cerebral blood flow in males caused by overall differences in blood flow (Esposito et al. 1996) and supporting the notion that increased cerebral blood flow leads to increased brain wave frequencies (Martinez-Tejada et al. 2021).

During the observation of 2D plants, compared with females, males exhibited significantly higher RA and RFA frequencies (in Fp1 and in Fp2, and Fp1, respectively). These results suggest heightened brain activity in the Brodmann area 10 of males when observing

Table 4. Comparison of sex-based results upon observation of each plant type.

			Male (n = 15)	Female (n = 15)		
Spectrum	Visual stimuli	Electrode	Mean ± *SD*		t	P value
Relattive alpha power spectrum (RA)[i]	Real plant	Fp1	0.165 ± 0.057	0.134 ± 0.03	2.734	0.011*
		Fp2	0.179 ± 0.03	0.148 ± 0.025	2.595	0.015*
	Artificial plant	Fp1	0.185 ± 0.043	0.157 ± 0.023	2.212	0.035*
		Fp2	0.179 ± 0.046	0.153 ± 0.025	1.913	0.066^{NS}
	Picture of a plant	Fp1	0.189 ± 0.461	0.149 ± 0.024	2.979	0.006**
		Fp2	0.181 ± 0.04	0.15 ± 0.022	2.666	0.013*
	Plant 3D model	Fp1	0.19 ± 0.044	0.144 ± 0.028	3.311	0.003**
		Fp2	0.177 ± 0.04	0.153 ± 0.032	1.864	0.073^{NS}
Rtelative slow alpha power spectrum (RSA)[ii]	Real plant	Fp1	0.012 ± 0.031	0.105 ± 0.017	2.334	0.027*
		Fp2	0.123 ± 0.271	0.103 ± 0.018	2.308	0.03*
	Artificial plant	Fp1	0.127 ± 0.035	0.109 ± 0.021	1.663	0.107^{NS}
		Fp2	0.123 ± 0.035	0.108 ± 0.02	1.373	0.181^{NS}
	Picture of a plant	Fp1	0.129 ± 0.033	0.105 ± 0.017	2.546	0.19^{NS}
		Fp2	0.124 ± 0.029	0.105 ± 0.015	2.227	0.34^{NS}
	Plant 3D model	Fp1	0.131 ± 0.331	0.101 ± 0.021	2.906	0.007**
		Fp2	0.124 ± 0.029	0.108 ± 0.223	1.659	0.108^{NS}
Relative fast alpha power spectrum (RFA)[iii]	Real plant	Fp1	0.058 ± 0.016	0.045 ± 0.007	2.892	0.007**
		Fp2	0.056 ± 0.014	0.045 ± 0.008	2.616	0.016*
	Artificial plant	Fp1	0.059 ± 0.017	0.045 ± 0.008	2.824	0.01*
		Fp2	0.056 ± 0.014	0.044 ± 0.007	2.754	0.012*
	Picture of a plant	Fp1	0.059 ± 0.015	0.044 ± 0.008	3.337	0.002**
		Fp2	0.057 ± 0.012	0.447 ± 0.008	3.175	0.004**
	Plant 3D model	Fp1	0.058 ± 0.014	0.042 ± 0.009	3.562	0.001**
		Fp2	0.535 ± 0.105	0.045 ± 0.011	2.031	0.052^{NS}

[i] RA refers to the relative alpha power spectrum: (8–13 Hz)/(4–50 Hz).
[ii] RSA refers to the relative slow alpha power spectrum: (8–11 Hz)/(4–50 Hz).
[iii] RFA refers to the relative fast alpha power spectrum: (11–13 Hz)/(4–50 Hz).
NS, *, ** Nonsignificant or significant at $P < 0.05$ and 0.01, respectively, according to independent t tests.
3D = three-dimensional.

Table 5. Comparison of SDM results during visual stimulation.

Visual stimuli	Being pleasant	Being natural	Being relaxed
		Mean ± *SD*	
Real plant	5.7 ± 0.9 a	5.6 ± 1.3 a	5.5 ± 1.1 a
Artificial plant	5.1 ± 1.0 b	4.2 ± 1.6 b	5.2 ± 0.9 a
Picture of plant	4.4 ± 1.2 c	3.3 ± 1.7 c	4.6 ± 1.1 b
Plant 3D model	5.0 ± 0.9 bc	3.9 ± 1.4 bc	5.0 ± 1.0 ab
F	7.509	11.555	3.962
P value	0.000***	0.000***	0.010**

, * Significant at $P < 0.01$ and 0.001, respectively, according to the one-way analysis of variance.

The statistical method used Duncan's post hoc analysis (a > b > c).

The lowercase letters indicate the activity group during the Duncan analysis.

3D = three-dimensional; SDM = semantic differential method.

2D leafy plants compared with that of females. These brain activity findings are consistent with the findings of a previous study that reported an increase in alpha waves in the prefrontal cortex during the observation of 2D images containing natural landscapes (Grassini et al. 2022). Additionally, the anterior cingulate cortex plays a regulatory role in various attentional processes and emotional processing (Bush et al. 2000). Anterior cingulate cortex activation is observed in response to both pleasure and displeasure, suggesting potential differences in brain responses to visual stimuli in natural environments exhibited by males and females (Lane et al. 1997). When observing 3D plant models, males exhibited significantly higher RA, RSA, and RFA frequencies than those of females in Fp1. These results suggest that as humans perceive and process stimuli, increased brain activity leads to increased glucose and oxygen consumption, resulting in increased oxy-hemoglobin levels (Watts et al. 2018). This finding aligns with the finding of a study that reported that, compared with females, males spend more time using computers and other devices, suggesting comfort and predictability during routine activities (Gülü et al. 2023).

All participants indicated that observing live plants was the most pleasant and natural, and they indicated that they felt the most tranquil when observing both live and artificial plants. These results are supported by studies that found that individuals experience a sense of tranquility and naturalness when viewing actual leafy plants and roses (Igarashi et al. 2015; Ikei et al. 2014), as well as a feeling of comfort during the observation of live and artificial plants (Jeong and Park 2021). Furthermore, emotional evaluations based on the presence or absence of plants showed significantly lower total mood disturbance scores on the mood state profiles and significantly higher scores for items related to calmness and steadiness, as assessed using the SDM, when participants engaged in activities such as observing live plants (Lee et al. 2021). These findings suggest that exposure to natural elements provides visual stimuli that contribute to psychological well-being, thus promoting a sense of stability and emotional balance.

Table 6. Variations in SDM responses based on sex and comparison of responses between sexes.

Evaluation	Visual stimuli	Male (n = 15)	Female (n = 15)	*t*	*P* value
		Mean ± *SD*			
Being pleasant	Real plant	5.6 ± 0.9 a	5.9 ± 1.0 a	−0.938	0.356^{NS}
	Artificial plant	4.8 ± 1.0 b	5.4 ± 0.9 ab	−1.890	0.069^{NS}
	Picture of a plant	4.2 ± 1.2 b	4.7 ± 1.3 b	−1.148	0.261^{NS}
	Plant 3D model	4.87 ± 0.9 ab	5.1 ± 1.0 ab	−0.737	0.467^{NS}
	F	4.752	3.230		
	P value	0.005**	0.029*		
Being natural	Real plant	5.4 ± 1.5 a	5.9 ± 1.0 a	−0.837	0.410^{NS}
	Artificial plant	3.7 ± 1.4 b	5.4 ± 0.9 ab	−1.884	0.070^{NS}
	Picture of a plant	3.2 ± 1.8 b	4.7 ± 1.3 c	−0.412	0.684^{NS}
	Plant 3D model	3.7 ± 1.5 b	5.1 ± 1.0 ab	−0.878	0.387^{NS}
	F	5.191	7.114		
	P value	0.003**	0.000***		
Being relaxed	Real plant	5.4 ± 1.0 a	5.5 ± 1.1	−0.162	0.872^{NS}
	Artificial plant	4.8 ± 0.6 ab	5.7 ± 0.8	−3.249	0.003**
	Picture of a plant	4.4 ± 1.0 b	4.8 ± 1.3	−0.917	0.368^{NS}
	Plant 3D model	4.9 ± 0.9 ab	5.2 ± 1.0	−0.739	0.466^{NS}
	F	3.218	2.020		
	P value	0.03*	0.122^{NS}		

NS, *, **, *** Nonsignificant or significant at $P < 0.05$, 0.01, and 0.001, respectively, according to the one-way analysis of variance.

NS, ** Nonsignificant or significant at $P < 0.01$, respectively, according to independent *t* tests.

The statistical method used Duncan's post hoc analysis (a > b > c).

The lowercase letters indicate the activity group during the Duncan analysis.

3D = three-dimensional; SDM = semantic differential method.

This study had several limitations. Examining various aspects of brain activity reveals differences across different areas. However, this study solely focused on measuring changes in the prefrontal cortex. Future research that compares and analyzes different brain regions would be beneficial to understanding the effects of plant visual stimuli on the human brain. Previous studies measured visual stimuli from plant types for an average of approximately 3 min, whereas the present study included participants who looked at plants for only 90 s. Thus, extending the duration of observation in future studies may yield different results. Participants remained seated while gazing at the plants. In future research, adopting a more comprehensive approach by directly observing plants and simultaneously confirming visual and tactile stimuli or incorporating olfactory stimuli using aromatic herbs would enable a more effective assessment of multisensory interactions. Furthermore, considering the use of head-mounted displays and devices, which bridge the gap between digital and natural environments, using 3D models for visual stimuli can contribute to deriving a more robust mechanistic basis for evaluating psychophysiological responses to immersive virtual reality technology. Additionally, because significant differences in psychophysiological responses based on plant types were not observed, future studies should include a wider range of plant types. For instance, comparing foliage and flowering plants and varying the density of plant arrangements may yield insights into their specific impacts on psychophysiological responses. Subsequent horticultural programs using foliage plants can be implemented in any environment, online or offline.

Conclusion

Although this study found no significant psychophysiological differences among the four plants in different forms, participants consistently reported higher psychological comfort and naturalness when observing live plants. These findings underscore the potential of 3D plant models, particularly in virtual environments like the metaverse, to provide enriching nature-related experiences for individuals who lack real-world access. Therefore, as shown by previous studies, the use of 3D models may serve as a source of personal natural experiences within the metaverse for those who have limited access to such environments in the real world. The 3D plant models may expand environmental education and nature-related experiences, thus contributing to changes in individuals' environmental perceptions and attitudes. Additionally, these findings demonstrate the potential for evolution toward a more comprehensive and innovative strategy to promote the connection between humans and nature by complementing and expanding existing methodologies for environmental education and therapeutic environments.

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