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Plant-inspired ambient display for sharing affect: Color, motion, and shape☆

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ABSTRACT

In this study, we propose a plant-inspired ambient display designed to convey the emotional states of remote users in both collaborative work and shared entertainment contexts. Drawing on the metaphor of plants commonly found in offices and homes, the system utilizes three plant-like modalities: color (leaf color), movement (overall shaking), and shape (leaf and stem bending). To examine the expressive potential of these modalities for conveying emotions, we created 24 plant emotion models, with two models for each of the 12 emotions selected from Russell's circumplex model of affect. These models were generated through a user study in which participants ($N = 20$) freely manipulated a mock-up. We also implemented a physical plant-imitating display using full-color LEDs, servo motors, and BioMetal Fibers (BMFs). Although the models did not strictly correspond to discrete emotion labels, evaluation results indicated that they provided a stable representation of specific affective regions (valence/arousal tendencies) within the circumplex model. Furthermore, comparative evaluations showed that the physical implementation successfully replicated the emotional impressions observed in the preliminary mock-ups. These findings suggest that plant metaphors have the potential to serve as a subtle and unobtrusive medium, for conveying broad affective tendencies in remote environments.

1. Introduction

In recent years, the demand for online environments has surged, largely driven by the COVID-19 pandemic [1]. The widespread adoption of telework and online education has made virtual interactions an essential part of daily life and work [2,3]. Additionally, the entertainment industry has increasingly shifted online, with streaming services, live music performances, online gaming, and virtual events becoming more prevalent. This transition has enabled people in remote locations to connect and share experiences beyond physical constraints [4].

However, a critical challenge persists across both professional and recreational virtual environments: the lack of nonverbal cues such as facial expressions, gestures, and vocal intonation, making it difficult to convey emotions effectively [5]. This limitation can hinder mutual understanding, impression formation, and the overall quality of communication, potentially reducing users' engagement and sense of connection [6,7]. For example, participants in online live events or multiplayer games may struggle to share emotions or foster a sense of unity [8]. To compensate for the lack of nonverbal signals in computer-mediated communication (CMC), users often rely on emoticons or emojis [9–11]. While effective for explicit communication, emojis often force users to define distinct emotions, leaving little room for ambiguity. In contrast, ambient displays leveraging plant metaphors can convey emotional states as subtle environmental changes. This ambiguity may allow for flexible interpretation by the receiver and could support a sense of connection without the pressure of direct interaction. Building on these advantages, this study proposes a plant-inspired ambient display designed to support such subtle emotional communication.

We focus on ambient displays as a promising method for expressing emotions. Ambient displays integrate naturally into everyday environments and communicate information in a subtle and non-disruptive manner [12,13]. They utilize phenomena such as condensation, airflow, or shadows to convey information unobtrusively [14–16]. In particular, with the increasing integration of plants in workplaces [17] and the rise in household plant ownership during the pandemic [18], plants have become familiar and comforting elements of daily spaces. In addition, plants are inherently unobtrusive, and changes in their appearance act as intuitive metaphors for their state or well-being. Thus, plant-based metaphoric expressions are expected to provide a natural means of conveying others' states and emotions.

Several studies have explored plant-based communication interfaces. David et al.'s "Infotropism" [19] and Kuribayashi et al.'s "Plant-Display" [20] used actual plants as expressive agents. Similarly, Botros

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et al.'s "Go and Grow" linked plant watering behavior to users' activity levels [21]. However, the slow response time of living plants limits their suitability for dynamic interactions. To address this limitation, Jarrett et al. explored artificial plants with shape-changing interfaces, demonstrating their potential to express emotions such as "sadness" through plant-like metaphors [22]. Extending this line of work, researchers have emphasized the importance of combining multiple modalities — such as color, movement, and shape — to convey a broader spectrum of emotions [23–25].

Building on these insights, we propose a plant-inspired ambient display designed to convey emotional states through metaphorical expression. Specifically, we develop a set of plant emotion models that utilize a combination of three modalities — color, movement, and shape — to express a range of emotions. We then implement a physical display capable of dynamically controlling these modalities to replicate the models in real time. Finally, we conduct user studies to examine how these plant-like expressions are perceived and whether the resulting impressions correspond to broad affective regions.

To guide our research, we formulated the following research questions (RQs) and hypotheses (Hs):

- **RQ1:** Can plant-inspired modalities (color, movement, and shape) be mapped as models to express human affective regions?
- **H1:** Specific combinations of the three plant modalities can convey specific affective regions (valence/arousal tendencies) in Russell's circumplex model in a way that is distinguishable from other emotional regions.
- **RQ2:** Can a physical plant-imitating display reproduce emotional expressions equivalent to those of a mock-up?
- **H2:** The physical plant-imitating display can convey affective regions equivalent to those conveyed by the mock-up videos, yielding consistent impression evaluation results.

This paper offers the following contributions to the field of entertainment computing and ambient media:

- **Establishment of a plant-based emotion mapping methodology:** We constructed 24 plant emotion models through a user-driven process, providing an empirically derived mapping between broad affective regions and plant-like modalities, including color, movement, and shape.
- **Realization of a multimodal organic interface:** We developed a physical ambient display that integrates RGB LEDs, servo motors, and BioMetal Fibers, demonstrating a hardware configuration capable of dynamically reproducing organic, plant-like expressions.
- **Validation of design transferability:** Through comparative user studies, we found that the affective impression patterns defined in preliminary mock-ups were largely transferred to the physical implementation. This suggests the potential of plant metaphors as a subtle medium for conveying broad emotional valence and arousal tendencies, rather than precise discrete emotions, in remote environments.

2. Related work

2.1. Challenges in remote environments

Teleworking, or remote work, has solidified its position as a prevalent mode of employment globally. By 2015, it was reported that 85 % of U.S. companies had embraced teleworking strategies [26]. In contrast, Japan, long working hours are the norm, and there is a work culture in which this is an indicator of loyalty and commitment to the company [27], which has made many companies hesitant to allow teleworking. The onset of the COVID-19 pandemic, however, prompted a significant shift. Following the declaration of a state of emergency in Japan during the summer of 2020, the prevalence of teleworking surged from 17.6 % to 56.4 %. This spike was transient, as the rate declined to 31.0 % once governmental pressure eased, only to rise again to 51.9 % in 2021 [28,29]. While teleworkers in Japan have appreciated benefits such as enhanced family time and productivity, challenges persist, including diminished communication with supervisors and peers, and heightened stress levels [30]. Dambrin highlighted these communication barriers and the complexities of managing employees' work status and well-being remotely [31]. The pandemic has seen a rise in the implementation of monitoring systems by companies skeptical of their teleworking employees. Examples include systems that prohibit the deactivation of cameras to visually monitor employees at home [32]. While these approaches enable a closer observation of employee activities, they raise privacy concerns and increase managerial burdens without effectively gauging employees' mental states, potentially straining professional relationships.

2.2. Ambient display

Ambient displays integrate seamlessly into their surroundings to deliver information in an intuitive, non-disruptive manner [13]. These displays often employ artistic methods, minimalistic lighting, and physical movement to subtly convey information [12]. Tsujimoto et al.'s "Ketsuro-Graffiti", which utilizes condensation patterns [14], and Sugiura et al.'s "Graffiti Fur", which creates fabric patterns through reversed fur movement [15], exemplify ambient displays blending into everyday environments. Colley et al. explored information conveyance through plant shadows [16]. With the increasing incorporation of greenery in offices [17] and the rise in household plant ownership during the pandemic [18], plants have become integral to daily life, making them viable candidates for ambient displays. David et al.'s "Infotropism" [19] and Kuribayashi et al.'s "PlantDisplay" [20] leveraged organic plant changes for communication, while Botros et al.'s "Go and Grow" linked plant watering to owner activity levels [21]. However, the slow response of living plants limits their utility for this research. Alternatively, artificial plants have been explored, as in Jarrett et al.'s ambient information system prototype [22]. They reported that users perceived a drooping plant as "sadness", indicating the potential of plant metaphors for emotional expression. In this study, we incorporate additional modalities to support a broader emotional spectrum and develop a plant emotion model based on Russell's circumplex model of affect.

2.3. Emotional expressions using multiple modalities

Extensive research has explored the depiction of emotions through various modalities. Song et al. proposed the Maru robot that combines color, sound, and vibration for emotional expression, and showed that the complementary use of these modalities improved emotional conveyance over single-modal approaches [24]. Bethel et al. emphasized the necessity of employing multiple modalities, such as body movement, shape, color, and sound, for emotional expression under external constraints [25,33]. Loffler et al. assessed the impact of different modalities, including color, motion, and sound, on emotional conveyance, affirming their combined effectiveness [23]. They reported that the different modalities effectively expressed various emotions.

While these prior studies demonstrate the effectiveness of multimodal approaches including auditory cues [23,25,33], in our study, we treat unobtrusiveness and ambient integration as core design requirements. Since plants are inherently silent organisms that quietly coexist in everyday environments, introducing artificial sounds would disrupt this "plant-like" quality and potentially interfere with the user's concentration, especially in teleworking contexts. Therefore, instead of using sound, our proposed system focuses on three natural plant-related modalities — color, movement, and shape — to convey remote users' emotional states while maintaining the subtlety required of ambient displays.

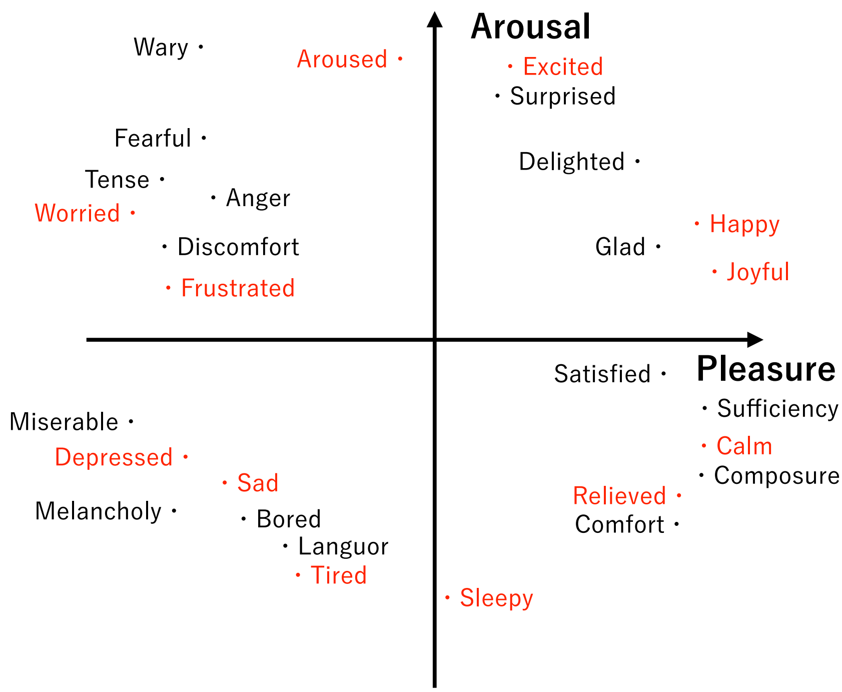

Fig. 1. Russell's circumplex model.

3. Plant emotion models

To develop a plant-imitating display for expressing users' emotional states, we formulated plant emotion models that integrate three natural modalities of plants: color, movement, and shape. This research was conducted in Japan, and the selection of emotional expressions and model construction were designed with Japanese-speaking participants in mind.

3.1. Emotions to express

We based our selection of emotions to be expressed by the plant-based display on Russell's circumplex model of affect, which organizes basic emotions along two dimensions: arousal and valence [34], and many adjectives were added in Japanese by Egawa et al. [35]. From this model, we selected twelve adjectives, three from each quadrant, that are appropriate for the work environment: excited, happy, joyful, aroused, worried, frustrated, tired, sad, depressed, sleepy, relieved, and calm, as shown in Fig. 1.

3.2. Investigation of expression method

To determine how the selected emotions could be appropriately expressed using the plant-imitating display, we adopted a user-driven experimental approach in which participants freely generated emotional expressions. For this experiment, we constructed a mock-up that participants could freely manipulate to vary three modalities: color (leaf color), movement (overall shaking), and shape (leaf and stem bending). The mock-up is shown in Fig. 2 and is based on an anthropomorphic plant toy known as "Pekoppa" [36].

First, colors and emotions are related. For example, based on Plutchik's wheel of emotions, red is assigned to anger, and blue to sadness [37]. Therefore, we prepared eight candidate leaf colors: red, orange, yellow, yellow-green, green, light blue, blue, and purple. These colors are located at the center of Plutchik's wheel of emotions [38]. In addition, we added five colors (ochre, brown, gray, black, and white) to which plants can actually change when they die or become sick: a total of 13 colors. To enable users to freely interchange the leaf colors, we cut leaf shapes from origami paper in these 13 colors and laminated them, as shown in Fig. 3.

The mock-up used in the experiment incorporated wires into the leaves and stems, allowing them to be freely bent. For movement and shape, participants were asked to manually manipulate the leaves and stems. We recorded their interactions using a video camera to explore the diversity of expressive behaviors.

Our participants were 10 male and 10 female students in their 20s. Before the experiment, we obtained written informed consent from all participants. We then explained the experimental procedure, including how to replace the leaf materials and how to manually bend the leaves and stems. To ensure they were comfortable with the mock-up, we provided a familiarization period where participants could freely practice these manipulations. Next, the participants were given a set of target emotions to express. The emotions were grouped based on the four quadrants of Russell's circumplex model: "excited, happy, joyful", "aroused, worried, frustrated", "tired, sad, depressed", and "sleepy, relieved, calm". Because of the semantic similarity among the emotions within each quadrant, the participants expressed sets of three emotions sequentially to distinguish their nuances. To avoid order effects, the presentation of the four quadrants was counterbalanced across participants, and they were allowed to express the three emotions within each quadrant in any order they preferred.

Our participants were 10 male and 10 female students in their 20s. Before the experiment, we explained its flow, how to replace the leaves, and how to bend leaves and stems. They signed a consent form. Next, they became accustomed to using the display by replacing the leaves and bending them and the stems. Next, the participants were given a set of emotions and were asked to express them freely. The emotions were grouped based on the four quadrants of Russell's circumplex model: "excited, happy, joyful", "aroused, worried, frustrated", "tired, sad, depressed", and "sleepy, relieved, calm". Because of the similarity among the emotions in each quadrant, the participants expressed sets of three emotions that belonged to each quadrant to distinguish among them. The order of presentation of the four quadrants was counterbalanced to avoid bias.

Fig. 2. Mock-up.

Fig. 3. Origami replacement leaves.

Table 1
Property of each element of plant emotion model.

Modality	Element	Property
Color	Leaf color	Red, orange, yellow, yellow-green, green, light blue, blue, and purple, ochre, brown, gray, black, and white
Movement	Overall shake	None, light shaking, slow light shaking, quick light shaking, large shaking, slow large shaking, and quick large shaking
Shape	Left-leaf angle	Under −90°, −90°∼−46°, −45°∼−1°, 0°, 1°∼45°, 46°∼90°, over 90°
	Right-leaf angle	Same as above
	Stem-bending position	Top, center, bottom
	Stem-bending direction	Front, back, right, left
	Stem angle	0°, 1°∼45°, 46°∼90°, over 90°

3.3. Development of emotion models

To derive common expressions across participants, we dissected the three modalities into seven specific elements: leaf color, overall shake, right and left leaf angles, stem bending position, direction, and angle, as shown in Table 1.

Based on the data collected from the 20 participants, we extracted common expression patterns to define representative models for each emotion. We calculated the frequency of selection for each of these seven parameters across all participants for each of the 12 emotions. For movement and shape, the parameters with the highest frequency were adopted as the representative definitions. Regarding leaf color, since choices tended to vary, we selected the top two most frequent colors for each emotion to capture a broader range of impressions. By combining these top two colors with the most frequent movement and shape parameters, we constructed two distinct models for each of the 12 emotions, resulting in a total of 24 plant emotion models.

We then aggregated the most frequently selected properties for each element to construct 24 emotion models. Following guidelines that emphasize the significance of color in emotional expression [24], each model was formulated by combining the two most prevalent leaf colors with the predominant choices for the other elements. In cases of equal frequency among options, we developed alternative models to encompass the variability, as seen in models expressing the emotion “excited”, where equal preferences for certain movements led to the creation of multiple variants. Table 2 shows the 24 plant emotion models and the combinations of the seven elements.

4. Impression evaluation I: Mockup-based evaluation

The purpose of this experiment is to verify whether the plant emotion model created in Section 3.2 can express human emotions. The participants were presented with images representing the model and asked to evaluate their impression of the model. For the model, we used a mock-up made of wire and colored paper based on a toy called “Pekoppa”, which was used in the experiment to collect the plant models described in Section 3.3.

4.1. Method

Our participants were 20 university students (10 males and 10 females) in their 20s who had not participated in the model derivation experiment described in Section 3.2. Written informed consent was obtained from all participants prior to the experiment.

To ensure consistent evaluation conditions, we presented video recordings of the plant emotion models rather than the physical prototypes. Each video clip was approximately 20 s long. To allow participants to fully inspect the structure, the motionless models were recorded from a 360-degree rotating perspective. In contrast, the moving models were recorded from four cardinal directions to clearly capture the dynamic changes in leaf and stem angles.

To maintain a highly controlled environment and prevent unintended interactions, acrylic partitions were installed between participants. All participants used identical 22-inch monitors, and the videos were presented using the screen-sharing function of Zoom. The video playback window was strictly calibrated to ensure that the plant models were displayed at life-size (i.e., the same physical dimensions as the actual prototype). Furthermore, to accommodate potential color vision deficiencies without formal screening, text labels indicating the leaf color were explicitly displayed within the video.

When evaluating the 24 plant emotion models, we carefully controlled for order effects. Specifically, half of the participants (n = 10) viewed the video clips in a randomized sequence, while the other half (n = 10) viewed them in the exact reverse order. After each presentation, participants rated their impressions of the 12 emotions selected in Section 3.1 on a 5-point Likert scale ranging from 1 (Strongly Disagree) to 5 (Strongly Agree). Videos were replayed as necessary if any playback issues occurred or upon a participant’s request.

4.2. Result

We performed a Shapiro–Wilk test on the impression ratings for the 12 emotions for each of the 24 plant emotion models. The results indicated that the data were not normally distributed. Therefore, we conducted a Friedman test, a non-parametric test, to compare the ratings among the 12 emotion adjectives within each model. Post-hoc multiple comparisons were performed using the Bonferroni method. Due to the non-normal distribution, comparisons were made using median values rather than means.

The medians of the 12 emotion adjectives for each plant emotion model are shown in Table 3. As a result, ten of the 24 plant expression models had adjectives with a median value of 5. For example, in the evaluation of model 24 which targeted “relieved” and “calm”, the

Table 2
24 plant emotion models and combinations of seven elements.

No.	Emotion	Leaf color	Overall shake (shaking)	Left-leaf angle	Right-leaf angle	Stem-bending position	Stem-bending direction	Stem angle
1	Tired,depressed,worried	Gray	None	−45°∼−1°	−45°∼−1°	Center	Front	46°∼90°
2	Tired	Brown	None	−45°∼−1°	−45°∼−1°	Center	Front	46°∼90°
3	Tired, depressed	Blue	None	−45°∼−1°	−45°∼−1°	Center	Front	46°∼90°
4	Tired, worried	Purple	None	−45°∼−1°	−45°∼−1°	Center	Front	46°∼90°
5	Sad	Blue	None	−45°∼−1°	−45°∼−1°	–	–	0°
6	Sad	Light blue	None	−45°∼−1°	−45°∼−1°	–	–	0°
7	Excited	Red	Quick light	1°∼45°	1°∼45°	Center	Front	46°∼90°
8	Excited	Red	Quick large	1°∼45°	1°∼45°	Center	Front	46°∼90°
9	Excited	Orange	Quick light	1°∼45°	1°∼45°	Center	Front	46°∼90°
10	Excited	Orange	Quick large	1°∼45°	1°∼45°	Center	Front	46°∼90°
11	Happy	Yellow	None	0°	0°	–	–	0°
12	Happy, calm	Yellow-green	None	0°	0°	–	–	0°
13	Joyful	Yellow	Quick light	1°∼45°	1°∼45°	–	–	0°
14	Joyful	Orange	Quick light	1°∼45°	1°∼45°	–	–	0°
15	Frustrated	Red	Quick large	−90°∼−46°	1°∼45°	–	–	0°
16	Frustrated	Orange	Quick large	−90°∼−46°	1°∼45°	–	–	0°
17	Aroused	Yellow	None	46°∼90°	1°∼45°	–	–	0°
18	Aroused	Red	None	46°∼90°	1°∼45°	–	–	0°
19	Sleepy	Light blue	None	0°	−45°∼−1°	Center	Front	46°∼90°
20	Sleepy	Light blue	None	0°	−45°∼−1°	Center	Left	46°∼90°
21	Sleepy	Purple	None	0°	−45°∼−1°	Center	Front	46°∼90°
22	Sleepy	Purple	None	0°	−45°∼−1°	Center	Left	46°∼90°
23	Relieved	Orange	None	0°	0°	–	–	0°
24	Relieved, calm	Green	None	0°	0°	–	–	0°

highest median value was 5 for "calm". This model also had a median value of 4.5 for "relieved", indicating that it gave impressions of both "relieved" and "calm". In addition, the median values for "relieved" and "calm" were significantly higher ($p < 0.05$) than for eight of the other ten emotions. In particular, "calm" was significantly higher than seven of the other ten emotions at the 1 % level. On the other hand, only "joyful" and "happy" were not significantly different from "relieved" and "calm".

These results indicate that model 24 gave the strongest impression of "calm", although it also gave impressions of "relieved", "joyful", and "happy". We defined these four emotions as expressed emotions when participants saw them. Like this model, three models had a median value of five for the target emotion in 24 plant emotion models: models 8 and 10, which targeted "excited", and model 24, which targeted "relieved" and "calm".

However, as was the case with model 24, these models do not necessarily make an impression of only a single emotion. When we compared the multiple emotions expressed in model 24 with Russell's circumplex model, we found that these emotions were in close proximity (Fig. 4). In Russell's circumplex model, when the two-dimensional region is divided into eight parts (a to h), model 24 expresses the emotions located in the a and h regions.

Thus, we conducted a similar analysis for the other plant emotion models. Adjectives, which had a median value of four or more and which were significantly different from 4 or more of the other 11 emotions, were defined as emotions expressed by the model.

The rationale for defining an "expressed emotion" as an adjective with a median of 4.0 or higher and significant differences from at least four other emotions is two-fold. First, on a 5-point Likert scale, a score of 4 corresponds to "Agree" and 5 to "Strongly Agree". A median of 4.0 or higher indicates that many participants tended to perceive the corresponding affective impression. Second, demonstrating a significant difference from at least four other emotions (more than one-third of the other 11 options) indicates that the model can successfully exclude distant affective regions. This criterion was used to identify models that appeared to convey a relatively specific valence/arousal tendency while intentionally tolerating the ambiguous overlap among semantically similar emotions (e.g., "happy" and "joyful"). We interpret this overlap not only as a limitation for discrete emotion recognition, but also as a characteristic of ambient displays that can leave room for user interpretation.

Our results showed that the 24 models represented a certain range of Russell's circumplex model, although they did not necessarily correspond to a single emotion. In addition,all eight regions shown in Fig. 4 were covered by the 24 models.

5. Plant-imitating display

Section 3.2 investigated how participants manually expressed plant emotion models using a mock-up. In this section, the functions of the three constituent modalities, namely color, movement, and shape, are determined based on 24 plant emotion models. Table 4 lists the properties of elements required to represent each modality. We develop a plant-imitating display that can dynamically control these modalities, as shown in Figs. 5 and 6.

5.1. Implementation

The plant-imitating display is engineered to emulate the required characteristics of the plant emotion models across the three modalities, utilizing actuators for execution as shown in Fig. 5. As shown in Fig. 6, controlled by an Arduino Uno R3, the display's capabilities for each modality are as follows:

5.1.1. Color

In the development of our 24 plant emotion models, leaf color plays a pivotal role, employing a palette of ten colors: red, orange, yellow, yellow-green, green, light blue, blue, purple, brown, and gray. However, gray and brown are difficult to represent using full-color LEDs. To facilitate dynamic color changes, full-color LEDs were utilized. However, the representation of gray and brown hues presented challenges with full-color LEDs, leading to their infrequent use—only one model utilized these colors. Moreover, other models effectively used blue and purple to convey emotions such as tiredness, depression, and worry, which prompted the exclusion of gray and brown in the final display design, focusing on the remaining eight colors.

For the display implementation, we opted for chip-type full-color LEDs with integrated microcontrollers due to their compact size and lighter weight compared to conventional bullet-type LEDs. The choice of material for the leaf screen was critical to ensure it did not absorb the LED light, could conform to the bending of the silicon tubing used as the main vein, and remained lightweight to complement the soft silicon

Table 3
Results for 24 plant emotion models:
E: excited, H: happy, J: joyful, A: aroused, W: worried, F: frustrated, T: tired, Sa: sad, D: depressed, Sl: sleepy, R: relieved, and C: calm.

Model no.	Targeted emotion	E	H	J	A	W	F	T	Sa	D	Sl	R	C	Expressed emotion	Part
1	W, T, D	1.0	1.0	1.0	1.0	**4.0**	3.0	**4.0**	**4.0**	**4.0**	**4.0**	2.0	2.0	W, T, Sa, D, Sl	d, e, f, g
2	T	1.0	1.5	1.5	1.0	3.0	2.0	**4.0**	3.0	**4.0**	**4.0**	3.0	**4.0**	Sl, C	g, h
3	T, D	1.0	1.5	2.0	2.0	**4.0**	3.0	**4.0**	**4.0**	**4.0**	**4.0**	2.0	3.5	W, T, Sa, D, Sl	d, e, f, g
4	W, T	1.0	1.0	1.0	2.0	**4.0**	3.0	**4.0**	**4.0**	**4.0**	**4.0**	2.0	3.0	W, T, Sa, Sl	d, e, f, g
5	Sa	1.0	1.0	1.0	1.5	**4.0**	2.0	**4.0**	**4.5**	**4.0**	**4.0**	2.0	3.0	W, T, Sa, D, Sl	d, e, f, g
6	Sa	1.0	1.5	1.5	1.0	**4.0**	2.0	**4.0**	**4.0**	**4.0**	**4.0**	2.0	3.0	T, Sa, D, Sl	e, f, g
7	E	**4.0**	3.0	**4.0**	**4.0**	2.0	3.5	2.5	2.0	2.0	1.0	2.0	2.0	E, A	b, c
8	E	**5.0**	3.0	3.5	**4.0**	2.5	**4.0**	2.0	1.0	1.0	1.0	1.0	1.0	E, A, F	b, c, d
9	E	3.5	3.0	3.5	3.0	2.5	3.0	2.0	2.0	2.0	2.0	3.0	3.0	–	–
10	E	**5.0**	3.0	**4.0**	**4.0**	2.0	3.5	2.0	1.0	1.5	1.0	1.5	1.0	E, A	b, c
11	H	2.0	**4.0**	3.5	2.0	2.0	1.5	2.0	2.0	2.0	2.0	**4.0**	**5.0**	C	h
12	H, C	2.0	**4.0**	**4.0**	2.0	1.0	1.0	1.5	1.5	2.0	2.0	**5.0**	**5.0**	H, J, R, C	a, h
13	J	**4.0**	**4.0**	**4.0**	**4.0**	2.0	3.0	2.0	2.0	2.0	1.5	2.5	2.0	E	b
14	J	**4.0**	**4.0**	**4.0**	**4.0**	1.5	2.0	2.0	1.0	1.0	1.0	2.0	2.0	E, H, J, A	a, b, c
15	F	**5.0**	3.0	**4.0**	**4.0**	2.5	**4.0**	2.0	2.0	2.0	1.0	2.0	1.0	E	b
16	F	**4.0**	**4.0**	**4.0**	**4.0**	2.0	**4.0**	2.0	2.0	2.0	1.0	2.0	2.0	F	d
17	A	**4.0**	**4.0**	**4.0**	**4.5**	2.0	2.0	1.0	1.0	1.0	1.0	2.0	2.5	E, H, J, A	a, b, c
18	A	**5.0**	**4.0**	**4.0**	**4.0**	2.0	**4.0**	1.0	1.0	1.0	1.0	2.0	2.0	E, H, J, A	a, b, c
19	Sl	1.0	2.0	2.0	2.0	**4.0**	2.0	**4.0**	**4.0**	**4.0**	**4.0**	3.0	3.0	Sa	e
20	Sl	1.0	1.0	1.0	1.5	**4.5**	2.5	**4.0**	**5.0**	**4.5**	**4.0**	2.0	3.0	W, T, Sa, D, Sl	d, e, f, g
21	Sl	1.0	1.0	1.0	1.5	**4.5**	3.0	**4.0**	**4.0**	**4.0**	**4.0**	2.0	3.0	W, T, Sa, Sl	d, e, f, g
22	Sl	1.5	1.0	1.0	1.5	**4.5**	**4.0**	**4.0**	**4.0**	**5.0**	**4.0**	2.0	2.0	W, T, Sa, D	d, e, f
23	R	**4.0**	**4.0**	**4.0**	3.0	2.0	2.0	2.0	2.0	1.5	1.5	**4.0**	**4.0**	H, J, R, C	a, h
24	R, C	1.5	**4.0**	**4.0**	2.0	1.0	1.0	2.0	1.0	1.0	2.0	**4.5**	**5.0**	H, J, R, C	a, h

Expressed emotions: Emotions with a median ≥4.0 and significant differences ($p < 0.05$) from ≥4 other emotions.
Part: Corresponding regions (a–h) in Russell's circumplex model (see Fig. 4).

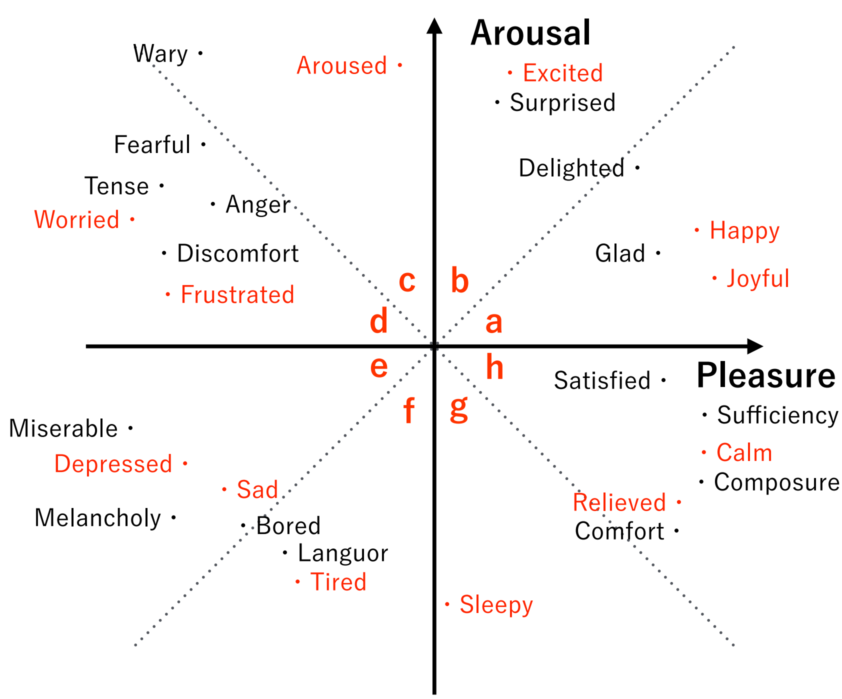

Fig. 4. Expressed emotion parts by model 24 on eight parts on Russell's circumplex model.

structure. Consequently, hanshi (traditional Japanese writing paper) was selected for its lightweight and flexible properties. As illustrated in Fig. 5, a leaf-shaped piece of hanshi paper is positioned atop the LED, creating a dynamic color-changing leaf effect.

5.1.2. Movement

In the development of our 24 plant emotion models, eight feature dynamic elements characterized by movement. These movements are categorized into two types: "quick light shaking" and "quick large shaking", each with four models. The "slow" movements corresponding to these "quick" movements are also provided, enabling the expression of movements with the four properties of "quick large shaking", "quick light shaking", "slow large shaking", and "slow light shaking".

The movement modality in our study is specifically designed to simulate the natural lateral movement of plants and is achieved through the use of a servo motor. As shown in Fig. 5, the setup involves attaching the base of a silicon tube, simulating a plant stem, to a servo motor arm. By oscillating the servo motor symmetrically to the left and right, we imitate the plant's shaking movement. The distinctions between "large" and "light" movements are controlled by adjusting the servo motor's rotation angle, whereas the "quick" and "slow" aspects are managed by modifying the angular velocity of the rotation. The

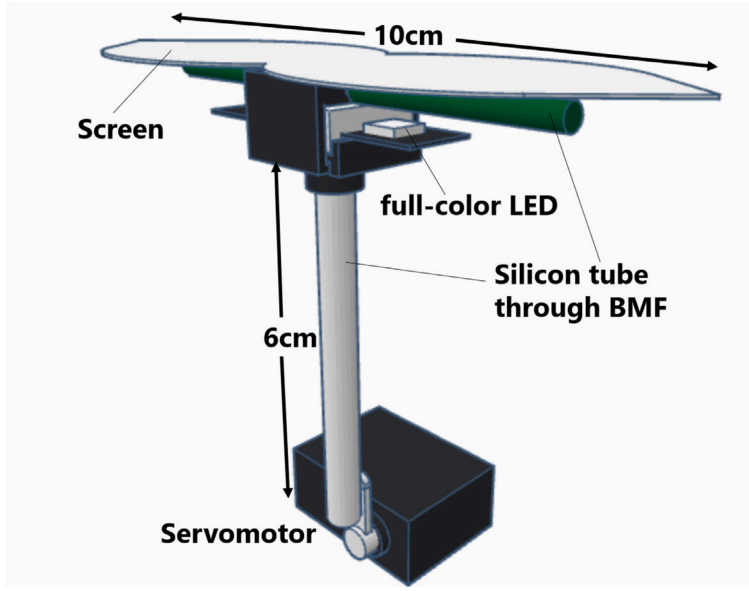

Fig. 5. Overview of plant-imitating display.

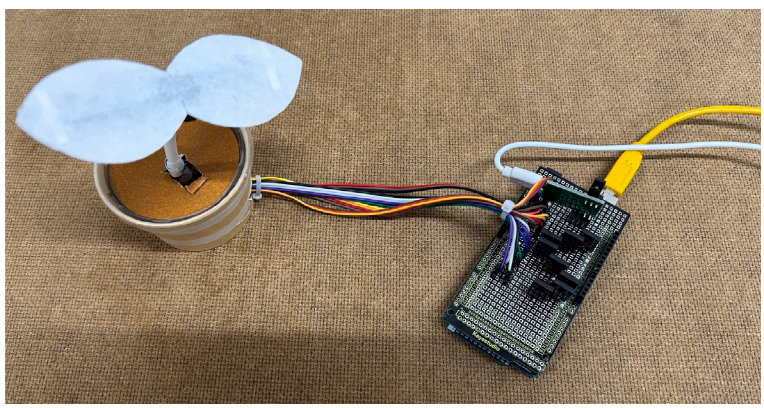

Fig. 6. Plant-imitating display.

Table 4
Property of each element of plant emotion model that can represent by plant-imitating display.

Modality	Element	Property
Color	Leaf color	Red, orange, yellow, yellow-green, green, light blue, blue, and purple
Movement	Overall shake	None, slow light shaking, quick light shaking, slow large shaking, and quick large shaking
Shape	Left-leaf angle	−90°∼−46°, −45°∼−1°, 0°, 1°∼45°, 46°∼90°
	Right-leaf angle	Same as above
	Stem-bending direction	Front, left

distinct parameters for each movement type (shaking amplitude and angular velocity) were determined through a quantitative user study, as detailed in Section 5.2. We utilized these optimized parameters for the final implementation and evaluation.

5.1.3. Shape

In the development of the 24 plant emotion models, the shape modality, specifically leaf and stem bending, plays a crucial role, with leaf bending employed in 20 models and stem bending in 12. The concept of shape in this context refers to the alteration from a plant's natural state through the bending of its leaves and stems. To imitate the autonomous bending behavior of a plant without external forces, we utilized BioMetal Fibers (BMF) within specially designed silicone tubes perforated with multiple holes [39,40].

BMFs are slender fiber actuators that contract upon heating, induced by an electric current, causing the silicone tube to bend. The direction of this bending can be manipulated by altering the placement of the holes through which the BMF threads. Additionally, the complexity of bending, including multidirectional bends, can be achieved by varying the number of holes utilized. The dimensions of the silicone tubes, serving as stems and main veins, were aligned with those of the plant-type mock-ups from Section 3.2. For the main veins of the leaves, we used 4.5 cm green silicone tubes with a 3 mm diameter and four holes were utilized, and for the stem, 6 cm white silicone tubes with a 5 mm diameter and seven holes. In our design, the green silicone tube, representing the leaf's main vein, features a central hole surrounded by three equidistantly spaced peripheral holes, as shown in Fig. 7. This configuration allows for the insertion of BioMetal Fiber (BMF) through each peripheral hole, facilitating controlled bending in both upward and downward directions when electrical current is applied. Consequently, this bending mechanism influences the attached half-paper leaf, enabling it to imitate natural leaf movements by altering its shape and orientation. Similarly, the white silicone tube, emulating

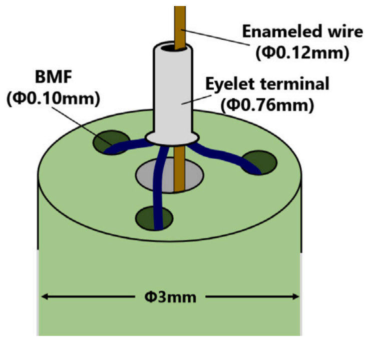

Fig. 7. Wiring of silicone tube as leaf main veins.

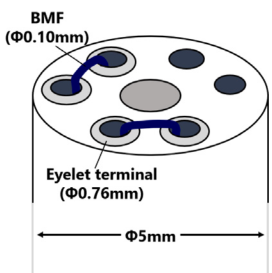

Fig. 8. Wiring of silicone tube as stem.

the plant's stem, is designed with two sets of holes positioned symmetrically around a central hole in three distinct directions, as shown in Fig. 8. Given that the plant emotion models necessitate stem movement in only two directions (forward and to the left), BMF is threaded through the corresponding holes to achieve the desired bending actions.

The extent of bending, both for the leaf and stem, is regulated by adjusting the voltage applied to the BMF. Specifically, leaf bending is calibrated to achieve two distinct positions, delineated by a 45° in both the upward and downward directions. Stem movement, on the other hand, is designed to span a range of 46°∼90°from the stem's central axis, oriented towards the front and left, to accurately represent the modeled emotions.

We conducted a preliminary technical verification with 6 participants to ensure the hardware components (LEDs and BMFs) could accurately render the intended parameters. The results confirmed that all colors and movements were distinguishable, except for slight confusion between yellow and yellow-green, which we addressed by adjusting the color definitions.

5.2. Determination of movement parameters

5.2.1. Experimental settings

To ensure distinct movement expressions, we conducted a preliminary experiment aimed at identifying optimal parameters for shaking amplitude and angular velocity.

The participants were nine males and five females in their 20s. Participants adjusted the shake characteristics of the physical plant-imitating display using the knobs of two semi-fixed resistors, which directly controlled the amplitude and angular velocity of the servo motor.

To account for potential effects of stem bending on perceived movement, participants were tasked with creating 12 distinct shaking patterns. These consisted of four shaking types ("quick large shaking", "quick light shaking", "slow large shaking", and "slow light shaking") under three conditions of stem bending (no bending, bending forward, and bending leftward). To ensure the elimination of any order effects that might bias the results, the sequence in which these 12 patterns were assigned to the participants was completely randomized.

Table 5
The average angle and speed of each movement.

Overall shake	Angle	Speed
Quick large shaking	44.07(SD 10.96)	284.9(SD 74.96)
Quick light shaking	12.00(SD 4.488)	217.0(SD 72.39)
Slow large shaking	46.14(SD 6.479)	80.04(SD 45.72)
Slow light shaking	10.86(SD 4.240)	28.22(SD 11.25)

After all 12 shake variations had been generated, we conducted a validation phase. The patterns they had just created were randomly re-presented to the participants, and they were asked to identify the intended type of shake shown. In cases where their identification did not match the intended shake pattern, participants were asked to readjust the parameters using the knobs and recreate the shake until the desired expression was reliably achieved. This rigorous manipulation check ensured the validity of the determined parameters for each movement type.

5.2.2. Result

The analysis of movement patterns in the plant-imitating display is detailed in the referenced Fig. 9, where the horizontal axis represents the amplitude of shaking and the vertical axis, the angular velocity.

The results are presented in Fig. 9. The horizontal axis shows the angular amplitude of shaking, and the vertical axis shows the angular velocity. Table 5 lists the means and standard deviations for both parameters in no stem bending. A t-test ($\alpha = 0.05$) was employed to assess the differences between types of shaking. The analysis revealed a significant distinction in angular velocity between the "quick" and "slow" shaking categories, such as between "quick and light" and "slow and light" shaking. Specifically, the average angular velocity for the "quick" category was recorded at 251.0, compared to 54.13 for the "slow" category. However, the difference in shaking amplitude was not statistically significant, with mean amplitudes of 28.04 and 28.50 for "quick" and "slow" shaking, respectively. This suggests that a discernible difference in angular velocity alone is sufficient to convey the intensity of shaking. Furthermore, a notable difference was observed between the "large" and "light" shaking groups in both amplitude and angular velocity. The "large" shaking group exhibited an average amplitude of 45.11 and an average angular velocity of 182.47, whereas the "light" shaking group had an average amplitude of 11.43 and an average angular velocity of 122.61. This indicates that both the amplitude and angular velocity must be increased to accurately convey the extent of shaking. The experimental participants' perception of shaking intensity appeared to be influenced by both the angular velocity and the frequency of oscillations. For instance, to achieve a "quick large shaking" effect, it was necessary to increase both the amplitude and angular velocity to compensate for the increased oscillation frequency required, compared to "quick light shaking".

There were no significant differences in stem bending patterns. The presence or absence of significant differences between the types of shaking produced the same results as for the absence of stem bending. This suggests that if the parameters obtained in this study are used to represent a sufficient difference in the magnitude and intensity of shaking, the effect of stem bending on the impression of the modality of movement should be small.

6. Impression evaluation II: Physical display-based evaluation

The purpose of this experiment was to verify whether the plant-imitating display implemented with full-color LEDs, servomotors, and silicon tubes through BMF in Section 5 can express human emotions. For comparison with Experiment I in Section 4, we used the same number of participants and evaluation method.

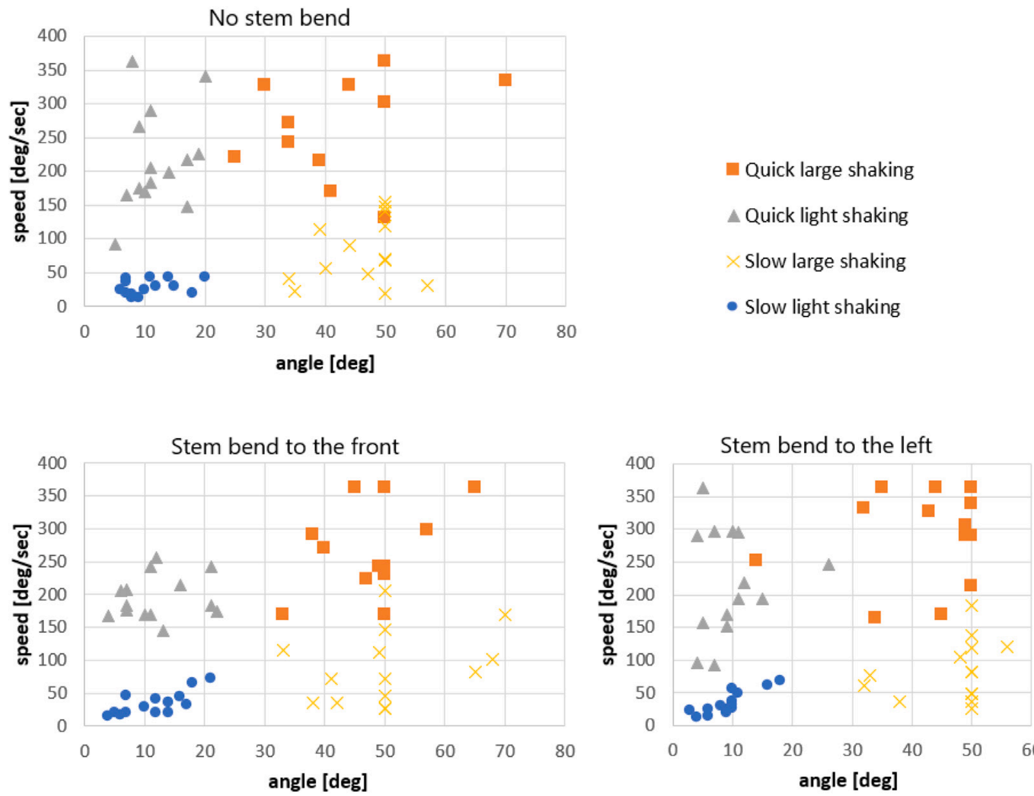

Fig. 9. Results of quantitative experiment of movement.

6.1. Method

The participants in this experiment were a completely new group of 20 university students (10 males and 10 females, with an average age of 22.1 ± 1.3 years) who had not participated in either the model derivation (Section 3.2) or the parameter setting studies (Section 5.2). Written informed consent was obtained prior to the experiment.

The key methodological difference from Experiment I was the method of stimulus presentation. Instead of viewing pre-recorded videos, each participant individually evaluated the actual physical plant-imitating display. The display was placed directly in front of the participant and operated in real-time to present the 22 plant emotion models (excluding the gray and brown models unrepresentable by full-color LEDs). The evaluation method was identical to Experiment I, utilizing a 5-point Likert scale for the 12 selected emotions. Each physical model was presented for approximately 5 s, aligning with the duration of the video clips in Experiment I, and could be replayed upon the participant's request.

6.2. Result

We performed a Shapiro–Wilk test on the 12 emotional impression ratings for each of the 22 plant emotion models and found that the data distribution was not normal. Therefore, we conducted Friedman's test, which is a nonparametric test, as in the experimental results in Section 4. We also performed multiple comparisons using the Bonferroni method. Since the data were not normally distributed, comparisons were made with the median instead of the mean.

The medians of the twelve emotion adjectives for each plant emotion model are listed in Table 6. As a result, 15 of the 22 plant expression models had adjectives with a median value of 5. For example, in the evaluation of model 13 which targeted "joyful" the highest median value was 5 for "joyful". In addition, the median values for "joyful" were significantly higher ($p < 0.05$) than for eight of the other 11 emotions and were significantly higher than seven of the other emotions at the 1 % level. On the other hand, there was no significant difference in the median value when compared to the three emotions "excited", "happy", and "aroused". This means that these three emotions may have been equivalent in intensity to "joyful". In particular, "happy" tended to be rated higher than the other two emotions. These results confirm that model 13 gives the strongest impression of "joyful", followed by "happy", as well as "aroused" and "excited".

Like this model, five models had a median value of five for the target emotion in 22 plant emotion models: models 5, which expressed "sad", and models 8 and 10, which expressed "excited", model 12, which expressed "happy" and "calm", and model 24, which expressed "relieved", "calm". However, as was the case with model 13, these models did not necessarily make an impression of only a single emotion, as with the results of Experiment I in Section 4. When we compared the multiple emotions evoked by model 13 with Russell's circumplex model, we found that these emotions were in close proximity, as shown in Fig. 4. In Russell's circumplex model, when the two-dimensional region is divided into eight parts (a to h), model 13 represents the emotions located in the a, b, and c regions. The emotions "joyful" and "happy", which were particularly strong impressions, were both located in the a-region.

We conducted a similar analysis for the other plant emotion models as in the experiment in Section 4. We defined the criterion for an "expressed emotion" as an adjective having a median value of 4.0 or higher and being significantly higher than at least four of the other 11 emotions. Our results showed that the 22 models covered specific regions within Russell's circumplex model, although they did not necessarily correspond to a single isolated emotion. In addition, all eight regions shown in Fig. 4 were covered by the 22 models.

6.2.1. Comparison with Experiment I

Comparing Experiments I and Experiment II, four models showed differences in their expressed-emotion sets: model 3 ("tired" and "depressed"), model 5 ("sad"), model 14 ("joyful"), and model 20

Table 6
Results for 22 plant emotion models:
E: excited, H: happy, J: joyful, A: aroused, W: worried, F: frustrated, T: tired, Sa: sad, D: depressed, Sl: sleepy, R: relieved, and C: calm.

Model no.	Targeted emotion	E	H	J	A	W	F	T	Sa	D	Sl	R	C	Expressed emotion	Part
3	T, D	1.0	1.0	1.0	1.0	**4.0**	2.5	**4.0**	**5.0**	**5.0**	**4.5**	2.0	3.0	W, T, Sa, D, Sl	d, e, f, g
4	W, T	1.0	1.0	1.0	1.0	**4.0**	3.5	**4.0**	**4.5**	**5.0**	**4.0**	2.0	3.0	W, T, Sa, D, Sl	d, e, f, g
5	Sa	1.0	1.0	1.0	1.0	**4.0**	2.0	**4.0**	**5.0**	**5.0**	**4.0**	2.0	3.0	W, T, Sa, D, Sl	d, e, f, g
6	Sa	1.0	1.5	1.0	1.0	**4.0**	2.0	**4.0**	**4.0**	**4.0**	**4.0**	2.0	3.5	W	d
7	E	**4.0**	3.0	3.0	**4.0**	2.0	**4.5**	2.0	1.0	1.0	1.0	1.0	1.0	E, A, F	b, c, d
8	E	**5.0**	3.0	**4.0**	**4.0**	2.0	**5.0**	1.5	1.0	1.0	1.0	1.0	1.0	E, J, A, F	a, b, c, d
9	E	**4.5**	**4.0**	**4.0**	**4.0**	2.0	**4.0**	1.5	1.0	1.0	1.0	2.0	1.0	E, A	b, c
10	E	**5.0**	3.0	**4.0**	**4.0**	2.0	**4.0**	1.0	1.0	1.0	1.0	1.0	1.0	E, J, A	a, b, c
11	H	1.0	**4.0**	**4.0**	2.0	2.0	1.0	2.0	1.0	1.5	2.0	**4.5**	**4.5**	R, C	h
12.0	H, C	1.5	**4.0**	3.0	1.0	2.0	1.0	2.0	2.0	1.0	3.0	**4.0**	**5.0**	H, R, C	a, h
13.0	J	**4.0**	**4.0**	**5.0**	**4.0**	1.0	2.0	1.0	1.0	1.0	1.0	3.0	2.0	E, H, J, A	a, b, c
14	J	**5.0**	3.5	**4.0**	**4.0**	1.0	2.5	1.0	1.0	1.0	1.0	2.0	1.0	E, H, J, A	a, b, c
15	F	**5.0**	2.0	3.5	**4.0**	1.5	**4.5**	1.5	1.0	1.0	1.0	1.0	1.0	E, A, F	b,c,d
16	F	**5.0**	3.5	**4.0**	**4.0**	2.0	**4.0**	1.0	1.0	1.0	1.0	1.0	1.0	E, H, A, F	a, b, c, d
17	A	2.5	**4.0**	**4.0**	3.0	1.0	1.0	1.5	1.0	1.0	1.5	**4.0**	**5.0**	H, J, C	a, h
18	A	3.0	2.0	3.0	2.5	2.0	**4.0**	2.0	1.5	2.0	1.5	2.0	3.0	–	–
19	Sl	1.0	1.0	1.0	1.0	**4.0**	2.0	**4.0**	**5.0**	**5.0**	**4.0**	2.0	3.0	T, Sa, D, Sl	e, f, g
20	Sl	1.0	1.0	1.0	1.0	**4.0**	2.5	**4.5**	**4.5**	**5.0**	**4.0**	2.0	3.0	W, T, Sa, D, Sl	d, e, f, g
21.0	Sl	1.0	1.0	1.0	1.0	**4.5**	2.0	**4.0**	**4.0**	**5.0**	**4.0**	2.0	3.0	W, T, Sa, D, Sl	d, e, f, g
22	Sl	1.0	1.0	1.0	1.5	**4.0**	2.0	**4.0**	**4.0**	**4.0**	**4.0**	2.0	2.0	W, T, D, Sl	d, e, f, g
23	R	2.0	3.0	3.0	3.0	2.0	1.5	2.0	1.5	2.0	2.0	**4.0**	**4.0**	–	–
24.0	R, C	1.0	**4.0**	**4.0**	1.5	2.0	1.0	1.0	2.0	1.5	2.0	**4.5**	**5.0**	H, R, C	a, h

Expressed emotions: Emotions with a median ≥4.0 and significant differences ($p < 0.05$) from ≥4 other emotions.
Part: Corresponding regions (a–h) in Russell's circumplex model (see Fig. 4).

("sleepy"). Five models (model 9 which expressed "excited", model 13 which expressed "joyful", model 15 which expressed "frustrated", and models 19 and 22 which expressed "sleepy") were not given an impression of the targeted emotion in Experiment I but were given it in Experiment II. On the other hand, four models (model 6, which expressed "sad", models 17 and 18, which expressed "aroused", and model 23, which expressed "relieved") were not given an impression of the targeted emotion in Experiment II, although they were given it in Experiment I.

7. Discussion

In this study, we explored the feasibility of using a plant-imitating display to convey remote users' emotional states through three modalities, resulting in the development of 24 plant emotion models. These models were designed to dynamically illustrate a range of emotions by varying color, movement, and shape.

Taken together, the results provide partial support for H1 and H2. Regarding RQ1, the mock-up-based evaluation showed that combinations of plant-inspired modalities were associated with broader regions of Russell's circumplex model, particularly valence/arousal tendencies, although they did not reliably correspond to single discrete emotions. Regarding RQ2, the physical-display evaluation showed generally consistent affective-region patterns with the mock-up evaluation, suggesting that these impression patterns were largely transferable to the physical implementation. Thus, the findings support the use of plant-inspired modalities for conveying broad affective regions, while indicating limitations in precise discrete-emotion communication.

7.1. Plant emotion models

The design of the plant emotion models revealed several consistent mappings between physical modalities and perceived emotions. First, the color patterns were generally consistent with established emotional representations [34,38]. High-arousal emotions (e.g., "excited", "frustrated") were predominantly mapped to red and orange hues, while low-arousal or negative emotions (e.g., "sad", "depressed") corresponded to blue and light blue.

Regarding movement, dynamic actions appeared to be important for representing high-arousal tendencies. For instance, "joyful" was expressed through "quick light shaking", whereas "frustrated" elicited "quick large shaking". This differentiation suggests a correlation between the magnitude of movement and the perceived level of "pleasure". The necessity of movement was further highlighted by the fact that static models (e.g., models 17 and 18) failed to effectively convey an "aroused" state. Furthermore, models lacking both movement and shape modalities (e.g., model 23 for "relieved") were perceived as less expressive, underscoring the value of integrating dynamic elements to enhance emotional distinctiveness.

Leaf shape also appeared to contribute to affective impressions: flat or slightly upward leaves were associated with relaxed or positive states ("calm", "happy"), downward-bending leaves with negative or low-energy states ("sad", "tired"), and upward-curved leaves with high-arousal positive states ("excited"). In contrast, stem-bending direction did not show a consistent effect on emotional perception (e.g., models 19 and 20 yielded similar impressions despite different stem directions).

Our results suggest that the proposed models can stably convey broader regions of Russell's circumplex model (i.e., valence/arousal tendencies), although discriminating closely located discrete emotions (e.g., "depressed" vs. "tired" vs. "sleepy") remains difficult. However, we argue that this difficulty in pinpointing discrete emotions is not a methodological flaw, but rather an inherent and desirable characteristic of ambient displays. By conveying broad affective regions instead of explicit emotion labels, the plant-imitating display allows for subtle, unobtrusive communication that leaves room for the receiver's interpretation. This ambiguity avoids the forced emotional sharing often associated with explicit emojis or text, thereby providing a more natural and less intrusive awareness of remote users' states.

7.2. Plant-imitating display

The physical plant-imitating display implemented 22 of the 24 models. While comparative evaluations showed a general consistency between the physical display and the mock-up, the transition to motorized actuation and hardware components introduced nuanced differences in perception.

In terms of color, while LEDs effectively rendered most hues, they could not accurately reproduce gray and brown, limiting the physical representation of certain low-arousal negative emotions (models 1 and

2). However, minor confusions, such as between yellow and yellow-green (e.g., model 12), appeared to have limited influence on the overall affective impression patterns.

Movement represented through servo motors had a pronounced impact. Precise, motorized shaking often conveyed a broader and more distinct range of high-arousal emotions compared to the manual shaking in the mock-up. For example, model 9 successfully conveyed "excited" and "aroused" in the physical display. Conversely, excessive motor speed sometimes overpowered the shape modality, causing unintended overlaps, such as perceiving "happy" or "excited" in a model intended solely for "frustrated" (model 16).

Finally, mechanical constraints slightly limited the shape modality. The physical display struggled to achieve leaf or stem bends exceeding 45° accurately. Although this diminished the expressivity of specific extreme poses, models with these limitations (e.g., models 20 and 22 for "sleepy") generally maintained their core emotional tendencies. This suggests that consistent movement may have helped preserve the core affective tendencies of some models, despite the restricted range of static deformation.

7.3. Limitation

This study has several limitations concerning the model definition and hardware implementation. First, regarding the plant emotion models, none of the models distinctly conveyed a singular emotion, primarily due to the semantic proximity of the chosen emotions within Russell's circumplex model. While this validated the model's utility for capturing broad emotional quadrants, it highlighted the difficulty in differentiating closely related labels (e.g., adjacent emotions). Second, linguistic variability in interpreting adjectives such as "aroused", "excited", and "frustrated" posed a challenge. Some participants sought clarification on these terms, underscoring the necessity of establishing a shared understanding or using clearer linguistic definitions to ensure consistent emotional impressions.

Regarding the physical implementation, the plant-imitating display exhibits three primary hardware limitations. The first is color reproduction; the current LED technology could not accurately produce specific hues like gray and brown, limiting the representation of models requiring these colors. The second is the mechanical range of motion. The BioMetal Fiber (BMF) actuators struggled to achieve bending angles greater than 45°, which constrained the expressiveness of models that rely on deep bending. Finally, the servo motors generated operational noise. Since the device is intended as a subtle, ambient communicator, this noise could disrupt the user experience and necessitates quieter actuation methods in future iterations.

Another limitation pertains to the demographic of our participant pool, which was restricted to Japanese university students in their 20s. The perception of plant metaphors and nonverbal emotional expressions is highly susceptible to cultural backgrounds, languages, and generational differences. Therefore, the generalizability of our current plant emotion models to broader age groups or different cultural contexts remains unverified. Future cross-cultural studies are necessary to determine how these metaphorical expressions are interpreted globally.

7.4. Application

This study presents a plant-inspired display that conveys broad affective tendencies through subtle physical cues. One possible application is online chat communication, where the display could provide a physical way to share affective cues beyond traditional emoticons. The tangible presence and friendly appearance of the display may help users become aware of remote users' affective states in a subtle and approachable manner.

As one possible design example, multiple displays could be arranged as a small "garden" in group chat scenarios, with each display corresponding to a remote conversation member. Such an arrangement may provide a peripheral cue to the overall atmosphere of the group, such as collective excitement, and may help users notice changes in an individual participant's engagement in the conversation.

The display may also be applicable to remote work, online learning, and other collaborative settings. By representing affective states through plant metaphors, it could function as a non-intrusive status indicator for remote workers or students. Such cues may invite timely responses or supportive communication without explicitly stating emotions or imposing direct pressure to respond to every displayed state.

Furthermore, the system could be explored in virtual events, such as online concerts, where it may visualize the collective enthusiasm of the audience. By physically representing aggregated affective cues, the display may help remote viewers sense the atmosphere of the event and feel more connected with other dispersed participants.

This method may also offer design implications for broader remote interactions, including personal relationships. For example, in long-distance relationships, the display may support lightweight emotional awareness between individuals and help maintain a sense of social connection despite physical separation.

8. Conclusion

In this research, we proposed a plant-imitating display designed to reflect the emotional states of remote users, leveraging the familiar presence of plants in both office and home environments. The display integrates three plant-inspired modalities: color (leaf color), movement (overall shake), and shape (leaf and stem bending). Participants were engaged in an experiment where they used a mock-up to represent 12 emotions derived from Russell's circumplex model, leading to the formulation of 24 plant emotion models encompassing leaf color, movement patterns, and bending angles of both leaves and the stem.

The comparative evaluation of the mock-ups and the plant-imitating display showed generally consistent impression patterns, suggesting that the affective impressions defined in the mock-ups were largely transferred to the physical implementation. These results indicate that the display can convey broad affective tendencies, particularly valence and arousal, within Russell's circumplex model. However, the findings do not necessarily demonstrate reliable communication of precise discrete emotions. Rather, they suggest the potential of plant-inspired physical cues as a subtle medium for expressing broader affective regions.

In the future, we aim to enhance the plant-imitating display by integrating it with data derived from facial expression recognition and posture analysis technologies. This advancement will facilitate a more nuanced exploration into the impact of the plant-imitating display on individuals' emotional states, particularly in remote settings, thereby broadening the application scope of this innovative display methodology in human–computer interaction and remote communication contexts.

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CRediT authorship contribution statement

Mai Kamihori: Writing – review & editing, Writing – original draft, Project administration, Methodology, Investigation, Data curation. **Rika Kawamura:** Writing – original draft, Visualization, Validation, Methodology, Investigation, Data curation. **Kouyou Otsu:** Writing – review & editing. **Yuichi Itoh:** Writing – review & editing, Project administration, Methodology, Conceptualization.

Ethical statement—studies in humans and animals

All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. This article does not contain any studies with animals performed by any of the authors. Informed consent was obtained from all individual participants included in the study.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the author used ChatGPT in order to improve readability and language. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Declaration of competing interest

The authors have declared no conflict of interest

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.entcom.2026.101163.

Data availability

Data will be made available on request.

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