Gaia: A Social Robot to Help Connect Humans and Plants

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Abstract: Interacting with plants has been shown to increase both physical and mental health outcomes and seemed obvious for many during such troubling times. Inevitably, plants died as a result of the owner's lack of awareness of their needs. Gaia, a social robot-planter, was created to communicate a plant's needs to its owner in an easy and enjoyable way. The final prototype, a multimodal interface, was designed to join natural language messaging with an emotive digital face and "voice." Creating a social robot that anthropomorphizes the user's plant to effectively communicate the plants' needs, build empathy, and create a stronger emotional bond between the plant and owner, leading to better outcomes for both.

1 INTRODUCTION

One strategy many individuals use to improve and personalize their space was to incorporate more plants. House plants not only elevate a room visually, they also provide comfort and have potential health and psychological benefits (Elings, 2006; Sabra, 2016; Seow et al., 2022). Alongside the rise in popularity of plant caretaking, there has been a parallel rise in products designed to help individuals care for their newly acquired plants (Clark, 2022). Increasingly, products are turning towards technology, often in the form of mobile applications, as a solution for common problems such as species identification, watering schedules, and troubleshooting if a plant's health begins to decline.

While the uptick in plant caretaking as a hobby has shown an upturn in houseplant sales, it has not been a revolution in the way humans interact with plants. Although plants are living things, they are treated more like decorations or accessories to a space rather than living companions. The relationship between a plant and its caretaker is entirely driven by the human that puts as much meaning into the plant as they want. The plant is unable to interact with or explicitly communicate with the caretaker. Instead, plants communicate their needs over days as their leaves and stalks droop yellow. Once a caretaker notices these changes in their plants' health, they must know what intervention to take; many owners have asked themselves the question, "Are these leaves turning yellow because of lack of or too much water?"

With these circumstances confusing communication, plant owners can find themselves stressed about the health of their plants while the plants find themselves under subpar care conditions. Our device Gaia, shown on Fig. 2a, transforms any houseplant into an evocative social robot that gives the plant a way to communicate its needs to the caretaker in an instant (Breazeal, 2003) using sensors and audio interface to check the plant's condition. Using soil and sunlight sensors, which measure the exact amount of moisture in the soil and the intensity of the light the plant is receiving, respectively, the robot describes the plant's needs to the user. Through the use of screens, emoticons, and sounds, Gaia anthropomorphizes the plant, making it easier for humans to understand its needs. Additionally, by giving the plant-robot the ability to express the same emotions as humans, it could increase the empathy a caretaker has for their plant, thereby making a caretaker more responsive (Urquiza-Haas and Kotrschal, 2015). Ultimately, the goal of Gaia is to make plant caretaking easier by allowing the caretaker to interact with the plant in novel ways involving emotion-based prompts.

1.1 Benefits of Plant Caretaking

Human-plant relations precede any written history. Not only have we relied on plants to survive, but

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plants have played an active role in human evolution, civilization, and urbanization. Humans have affected plant evolution in a similar manner – through cultivation and agriculture, we have developed a co-dependence with the plant kingdom (Van der Veen, 2014).

As a result of this close relationship with plants, humans can receive a multitude of benefits and range of interactions – from simply being around plants to actively gardening (Elings, 2006; Sabra, 2016). In passive interaction environments (e.g., plants in an office setting), being in the presence of vegetation has shown to improve cognitive functioning, attention maintenance, creativity, and even happiness (Chien et al., 2015; Seow et al., 2022). When workplaces have abundant greenery, employees reported decreases in negative health effects like headaches and tiredness and allowed workers to recover from stress more quickly (Elings, 2006). Additionally, successfully caring for a houseplant can provide a feeling of control in a world where daily stress leaves people feeling increasingly unmoored (Sabra, 2016).

In activities involving greater interaction, like gardening, there are physical benefits, such as lowering the risk of heart disease, in addition to the robust psychological benefits. Considering mental health, gardening has been seen to increase self-esteem and can provide a sense of belonging and self-worth. Therapeutic horticulture, or the use of gardening and cultivating to promote well-being, has been incorporated into social and clinical work as an alternative therapy. In therapeutic settings, gardening provides an environment where people can be mindful and intentional and, as a result, can become more aware of their surroundings, recognize stressful triggers, practice self-regulation, and have a healthy outlet for their frustration (Chien et al., 2015; Elings, 2006; Sabra, 2016).

1.2 Social Robot and Human-Plant Interaction

Relying on Social Robot principles of empathy and interaction, Gaia seeks to build a stronger bond between a caretaker and their plant, making it easier and more fun to maintain the health of one's houseplants. In this context, our team uses the Socially Evocative definition for a social robot, described as anthropomorphized robots to encourage humans to interact with them in a more natural way (Breazeal, 2003). As a result of its interactive nature, a social robot could provide several psychological benefits. Robinson et al. suggest that interactions with social robots could decrease levels of loneliness, and, more recently, a meta-analysis of the use of social robots with older adults found that interactions with social robots could also lower levels of agitation and anxiety (Robinson et al., 2013; Pu et al., 2019). By turning the simple houseplant into a social robot, we seek to capture the health and wellness benefits from both interacting with a social robot as well as plant caretaking.

Gaia is not the first attempt to create a device allowing humans to interact with plants on a deeper level. Such existing devices compose a subset of what is considered Living Media Interfaces (LMI). Merritt et al. define LMI as "interfaces that incorporate living organisms and biological materials into artifacts to support interaction between humans and digital systems,". Key features of an LMI include a digitally controlled input/output communication (I/O), the ability to communicate a feeling, and facilitation of human interaction (Merritt et al., 2020).

Other projects have sought to create interfaces using 'I/O Plant' design patterns for allowing a plant to directly affect actuators (Kuribayashi et al., 2007b). With Plantio, researchers used sensors that measured a plant's biopotential, allowing the plant to "wake up" when it was stimulated (using LED lights) (Kuribayashi et al., 2007a). More recently, researchers at the MIT Media Lab developed a device and framework for plant-based interfaces (Seow et al., 2022). By attaching electrodes, actuated by a sensor, to a *mimosa pudica* plant, researchers were able to simulate natural impulses and provide a plant-based interface that displayed information on air quality through opening and closing *pudica's* leaves (Seow et al., 2022).

The closest work to our approach was carried out by Angelini et al. (Angelini et al., 2016), where three different augmented plants based on user personas were designed. The difference resides is that we focused on the social features of the plant and its ability to trigger emotions using humanoid voice and emoticon faces while caring for the plant. Additionally, social aspects in human-plant interaction research (Chang et al., 2022), involving emotions and voice in one single system was not investigated before this work.

Our design focus was to create a nurturing system - as defined by Aspling et al. as "interfaces that support the well-being of the plant through greater expression of need, anthropomorphization, and creating emotional bonds with humans" (Aspling et al., 2016). One example of a nurturing system is 'My Green Pet' that allows the measurement of the physical contact children made with the plant (e.g., hitting, stroking, tickling, etc.) and output audio and visual information to help children identify the plant as a living organism (Hwang et al., 2010). However, their design sought to hide electric components to emphasize the organic

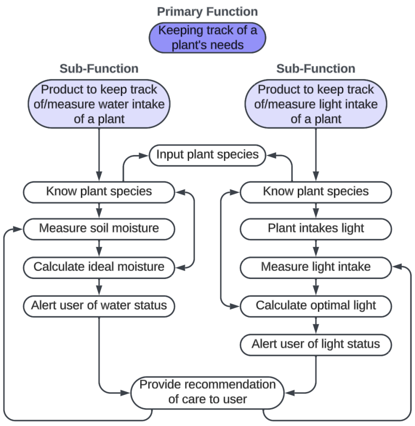


Figure 1: Functional analysis.

nature of the plant (Hwang et al., 2010). With Gaia, we designed the device as a nurturing system where the components would be visible while still creating an emotional bond.

2 IDEATION & EARLY TESTING

2.1 Ideation

Ideation started with a storyboard depicting a user's journey: a person initially struggles to care for houseplants, but finds success with an interactive plant. This plant not only self-assesses its needs but also communicates them effectively to the owner. The design prioritized making the user experience fun and exciting.

A functional analysis (Fig. 1) identified the device's main functions and user interaction considerations. This analysis informed a morphological chart, listing functions with multiple solution options (Roozenburg and Eekels, 1995). From this, three top solutions were selected for further analysis: 1) Minimalist Wall Art, with the plant on an interactive wall; 2) Maximum Interaction, where the plant, like a robotic cleaner, moves on wheels with obstacle sensors for light-seeking; 3) Balanced Approach, keeping the plant in a pot but with enhanced human-plant interaction features.

Using the morphological chart, we created low-fidelity sketches for the device's initial prototype. This process involved selecting features, determining module size and placement, and conceptualizing the device's overall visual design. We also discussed user interaction and the physical interface. Initially, the design consisted of a discrete stand the plant would be set on with water and light information surrounding the plant. Ultimately, we decided that separating the plant from the information felt too artificial. Having the information attached to the plant's pot made it feel like it was being communicated from the plant itself. Gaia aims to evoke the sense of caring for a robotic pet, akin to a Tamagotchi, where it communicates its feelings and care needs back to the user.

2.2 Early Stage Prototype Testing

2.2.1 Research Questions

During the initial design of Gaia, when we had an understanding of the main functions of the device as well as the general structure, we had several usability questions that we wanted to validate: 1) Can users correctly interpret the emoticons we chose to represent the plant's various states?, 2) What is the best way for the plant to communicate its status on the LCD screen? Should it display natural language phrases (e.g., "I need water") or exact sensor readings (e.g., "Soil Moisture 25%")?, and 3) Do users understand how to use the buttons on the device?

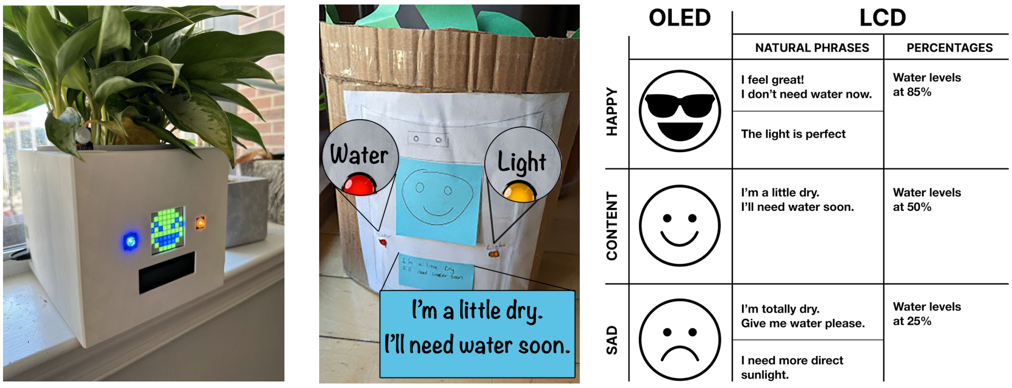
To answer these questions, we created a rapid paper prototype of the device using cardboard, LED button modules, and sticky notes (see Fig. 2). A cardboard frame was made to simulate the device, complete with LED buttons. Sticky notes on the cardboard prototype had drawings of the various emoticons and status messages on them. During the test, when a participant interacted with the mock device, a researcher would switch the sticky notes to reflect the correct status. All testing sessions were conducted in person.

2.2.2 Participants

For the initial test, we recruited four participants aged 23 to 42 years old. Prior to the test, participants were asked to gauge their experience with caring for houseplants. Three of the participants owned multiple houseplants, and the fourth had plants in the past but was not a current owner. None of the participants described themselves as very confident with their ability to keep their plants alive; all participants had used Google to help them care for their plants, with two of the participants reporting they currently use mobile apps to track a watering schedule for their plants.

2.2.3 Task List

The usability test focused on assessing how well participants would use different information to inform plant care. The tasks consisted of checking the water and light levels of the plants, with one set displaying information in natural language (NL) phrases and



(a) (b) (c)

Figure 2: (a) Gaia in operation with a plant inside. (b) The cardboard prototype used in the initial testing: Sticky notes act as interchangeable screen states, (c) Different faces and screen states tested in the usability session.

the other set displaying information with exact sensor readings. All participants completed both sets of tasks. The tasks can be seen below:

1. **Check the Water Level of the Plant.** "If you wanted to check the current water levels of your plant, how would you do that?"
   (a) *Show user natural phrase messages or percentage messages*: "Based on this information, how would you care for your plant?"
2. **Check the Light Levels of the Plant.** "If you wanted to check the current light levels of your plant, how would you do that?"
   (a) *Show user natural phrase messages or percentage messages*: "Based on this information, how would you care for your plant?"
3. **Verify the Different States of the Plant.** "Imagine you walked by your interactive plant and saw this face on the screen. What would that make you think of?" *(Default Happy State)*
   (a) "How would you care for your plant after seeing that?"
   (b) "What about this face?" *(Change to Sad State)*
   (c) "How would you care for your plant after seeing that?"

2.2.4 Results

Due to the small number of participants, we need to be considerate of the level of confidence we give the test results, however, we were able to pull out high-level trends based on the interactions we saw.

1. **Interpretation of Emoticons.** Participants consistently demonstrated an ability to interpret the emoticons representing the plant's various states. The emoticons were often the first element noticed, with participants quickly understanding the emotions conveyed before reading the LCD messages. This suggests that the chosen emoticons effectively communicated the plant's needs, aligning well with the intended design of Gaia.
2. **Comparing NL Phrases vs. Exact Sensor Readings.** Participants exhibited high confidence in responding to NL phrases (e.g., "I need water"). They understood and acted upon these messages with clearly and consistently, indicating a preference for this mode of communication. The response to exact sensor readings (e.g., "Soil Moisture 50%") was mixed, with some participants gave the plant a little bit of water while other waited to give the plant more water. Participants were less confident about the necessary care, indicating some ambiguity in interpreting these readings. This suggests that NL phrases are more effective in communicating plant needs to users.

Our results led us to use natural language (NL) phrases for user information display. NL phrases improved participants' understanding of plant care and needs. Our set sunlight and soil moisture thresholds, coupled with corresponding messages, promoted a natural watering schedule—allowing soil drying before thorough watering, instead of constant semi-hydration. Additionally, NL phrases added "personality" to plants, making them seem more like companions than mere health maintenance devices for participants.

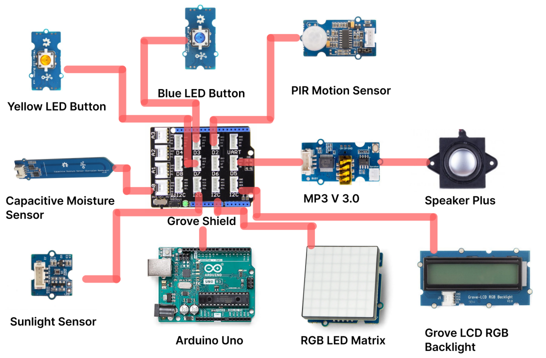


Figure 3: Electrical connections from Arduino Uno to modules.

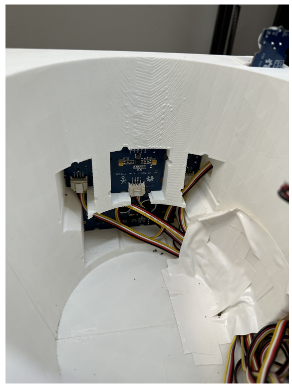


Figure 4: The interior look of the 3D-printed plant pot shell created using the Creality Ender 3.

3 GAIA PROTOTYPE

Gaia, controlled by an Arduino Uno and Grove Seeed modules, interacts with plant owners using sensors. As the owner approaches within 3m, the PIR Motion Sensor activates, triggering the Sunlight and Capacitive Moisture Sensors to measure light and soil moisture. The plant's status is communicated via the RGB Matrix embedded in the shell, displaying faces indicating water and light levels. Owners can check these levels using two LED buttons; the blue for water on the left and the yellow for sunlight on the right of the RGB Matrix. We chose these colors for their strong association with plant needs. Pressing the buttons displays a face, a message on the LCD RGB backlight, and plays a sound reflecting the plant's 'mood,' produced by an MP3 player module, a Micro SD card, and a speaker. The outer square shell, 3-D printed and shown in Fig.3, houses the modules and includes a space for a flower pot, making plant placement easy.

3.1 Interface Design

3.1.1 3D Printed Plant Shell

The initial 3D print shell, that was circular, did not enable a secure fit to the Arduino modules. We switched to a rectangular shape shell (17.5 (W) x 19.5 (L) x 16 cm (H)) to comfortably fit all Arduino modules and to protect them from water and soil (Fig. 4). The outside rectangular shell was designed to fit any 6-inch pot or less. The pot easily slides in and out to allow for maintenance. The pot shell was printed using a Creality Ender 3 3D-printer, with white PLA filament. The white was chosen to blend in with other planters that the owner could have in their home, also allowing for the lights to bounce off the white for better visibility. The LCD buttons, RGB Matrix, and LCD RGB screen were placed in the front to represent the face of the plant while the speaker was located in the back of the device.

3.1.2 Sound Design

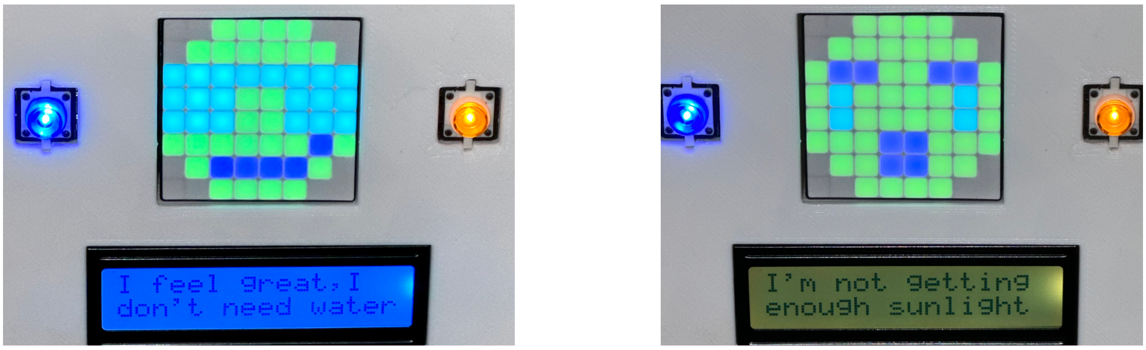
The sound design for Gaia has two primary goals, first to reinforce the visual information being presented about the status of the plant, and second to foster an emotional connection between the user and the plant. Ideally, the sound design would transform Gaia from a common house or decorative plant into something that is cared for and holds emotional value that in turn, drive more intentional care for the plant.

The sound design was modeled after something that was already familiar to people. Cute and friendly robots, have existed in the media for decades and produce strong feelings in the people that interact with them (Dou et al., 2021). This allowed the design to tap into an already existing mental model and resulted in the creation of a childlike and expressive voice that could convey and amplify both the negative and positive emotions desired.

Both Positive and negative sounds were implemented. Negative audio feedback would prompt negative feelings and motivate users to quickly resolve any issues in the plant's environment. Conversely, positive audio feedback would provide a positive emotional reward, reinforcing behavior (Jolij and Meurs, 2011).

3.1.3 Visual Design

The insights and findings gathered from the usability testing sessions were implemented into the design of visual displays of the RGB Matrix and LCD screen. Participants in the usability study responded more to NL messages (e.g., "I feel great, I don't need water") than sensor readouts (i.e., percentages). We designed the LCD messages to sound more conversational while still remaining within the 32-character



(a) (b)

Figure 5: Examples of different screen states based on soil moisture and sunlight levels: (a) Sufficient moisture level state with happy face and message, (b) Insufficient sunlight state with sad face and message.

constraint of the LCD screen. The usability study also uncovered that the design of the 'face' on the RGB Matrix was a very salient feature and reinforced the message on the LCD screen.

3.2 Modes

3.2.1 Motion Sensor Mode - Plant Wakes Up

The plant when motion is not detected is in a sleep state, only showing a message on the LCD that states "zzzzzzzzz". As the plant owner walks past the plant the sensor will trigger and they are able to glance over and look at the overall health of the plant as seen in Fig. 5. They can see the RGB Matrix which will display a range of emotive faces depending on the water level and light level. If both water and light needs are met, it will display a happy face. If only one need is met, it will show a neutral face, communicating that it needs care soon. If both needs are unmet, it will display a crying face to show that it needs to be tended to. This 'plant wake-up mode' is intended to help the user understand the overall health of the plant with a quick glance as they go about their day, and can also serve as a reminder that the plant needs tending to. In this mode, no any sound or voice output is provided by Gaia.

3.2.2 Moisture Sensor Mode - Blue LED Button Pressed

When the plant owner is interested in learning about the water level they can walk over to the plant pot and press on the blue LED button. The button will read the moisture level of the soil, the RGB Matrix will then show the feeling of the plant based on the level. If the moisture level is $\geq 50\%$, a happy face with sunglasses with a happy sound appears, and a message on the LCD that states "I feel great, I don't need water." If soil moisture is between 15 and 50%, a happy face accompanied by a contented sigh is displayed with a message on the LCD that states, "A bit dry, need water tomorrow," to communicate that it will be tending to tomorrow. If soil moisture is $< 15\%$, the matrix will show a crying face, a sad sound will play, and an LCD message will display, "I'm totally dry, I need water!" If the plant owner sees the last message, the intention is that they will water the plant.

3.2.3 Sunlight Sensor Mode - Yellow LED Button Pressed

When the plant owner is interested in learning about the amount of sunlight their plant is receiving, they can walk over to the plant pot and press the yellow LED button. The button will read the light levels and the RGB Matrix will then show the feeling of the plant based on the level. If the light level is $\geq 50\%$, it will show a happy face with sunglasses on, the LCD will display a message stating "I am getting enough light!" and the speaker will play a happy sound. If the light levels are $< 50\%$ the RGB Matrix will show an unhappy face, a message stating "I'm not getting enough sunlight," and a sad sound. This 3D prototype was tested in a second user study described below.

4 USER STUDY

4.1 Participants

Eight participants (Average Age: 29.6 (SD:9); Gender: 3 F, 4 M, 1 prefer not to say) were recruited for this study. They were all Bentley University students and were compensated for their time.

4.2 Usability Test

Participants were instructed to interact with Gaia by responding to the needs of the plant. They were sitting in a dim room to be able to modulate the light level using a nearby lamp and have a complete interaction experience in a single study session and were provided with a bottle of water and a lamp as described in the instructions: *"This plant has essential needs for its growth. The plant pot that you see has buttons and displays. Please take some time to examine this plant pot and interact with it. Try to satisfy the plant's needs by following visual and audio prompts from the pot by using the water and the lamp provided"*.

After the interaction with Gaia, they were asked to assess the voice using the Self-Assessment Manikin (SAM) (Bradley and Lang, 1994) with a five-point scale and evaluate the overall usability using the system usability scale (SUS) (Brooke et al., 1996). The SAM is a non-verbal pictorial scale that directly measures the valence, arousal, and dominance dimensions associated with a person's affective reaction to a wide variety of stimuli, including visual, auditory, and tactile (Ziat and Raisamo, 2017; Ziat et al., 2020). The SUS is used to assess several usability attributes such as effectiveness, efficacy, and satisfaction.

4.3 Results

All participants successfully interacted with the device buttons, indicating no issues in understanding their functionality. This confirms the usability of the button interface in the prototype design. The mean SUS score of 77.2 with a 95% confidence Interval [68 - 87], significantly ($p < .05$) above the average (68), reflects a high level of usability and user satisfaction with Gaia. It is equivalent to a B on the Sauro/Lewis SUS grading curve with a corresponding grade range from C to A+ (Lewis and Sauro, 2018).

The SAM results showed that 75% of participants felt in control and excited, with 50% reporting happiness (Fig. 6). Participant feedback indicated confusion over delayed responses; three participants expected immediate changes in the plant's state. For instance, two noted: "After watering, the hydration level showed happy, but it turned dry again after 10-20 sec," and "The delayed feedback might lead to overwatering."

Most participants liked the happy voice but found the unhappy/whining voice annoying or excessive. Yet, the voice feature was viewed as a social icebreaker, with a participant noting its suitability for business or social settings with unfamiliar guests. Also, several participants were intrigued by the device's potential to assist those struggling with plant care, with comments like, "Very interesting device, though not a plant person," and "Seemed incredibly helpful for someone who has never really grown plants."

5 CONCLUSION AND FUTURE RESEARCH

At present, Gaia embodies the foundational concept of transforming a living plant into a simple social robot, drawing from the broader context of LMIs as defined by Merritt et al. (Merritt et al., 2020). Our ambition, given more resources and time, is to enhance Gaia in two critical areas: offering more sophisticated plant care and advancing its social robot features.

To help plant owners care for their plants, Gaia currently communicates a plant's needs by taking readings from either the soil or moisture sensor and comparing the values to a set of predetermined thresholds. This method of communication, while effective, doesn't account for the diverse requirements of different plant species. Each species has its own optimal care conditions, some might want dry soil for long periods of time or to be always kept above 50% soil moisture respectively. In future versions, we aim to incorporate a species selector, inspired by the species-specific considerations that have been notably absent in earlier projects (Kuribayashi et al., 2007a; Kuribayashi et al., 2007b; Seow et al., 2022). This functionality will enable Gaia to provide tailored care, adjusting sensor thresholds for individual plant species, ensuring optimal growth conditions. Furthermore, there are additional sensors that could be added to Gaia that would increase the level of plant care, such as humidity and temperature sensors. These would work in conjunction with a species selector to ensure any plant could be given its optimal environment.

Gaia's current iteration, with its emoticons and natural phrases, is just the beginning of what we envision for its social robot capabilities. Moving forward, we plan to integrate more immediate interaction features, addressing the delay issues identified in our user study; which were related to the source of unhappiness expressed by some of the participants as they expected an instantaneous interaction. This development will take cues from the augmented plants of Angelini et al. (Angelini et al., 2016) and the nurturing system approach defined by Aspling et al. (Aspling et al., 2016), further enhancing Gaia's ability to forge a strong emotional bond with users by giving it a stronger personality and using more complex interactions. The introduction of a "Party Mode", a function

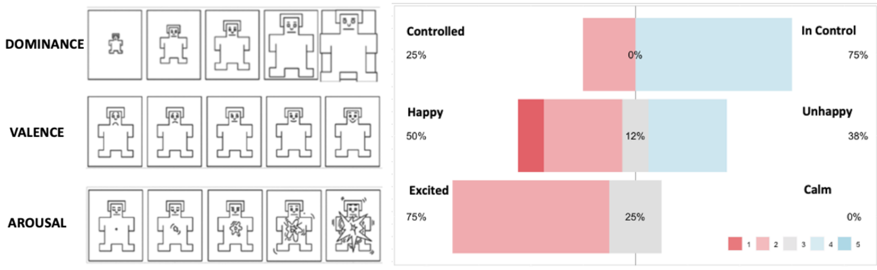


Figure 6: Left: SAM scale, Right: SAM results for the three affective dimensions: Dominance, Valence, and Arousal.

where Gaia would play music and simulate a dance party, and a richer library of animations and sounds will enable Gaia to express more lifelike and nuanced states, surpassing the level of interaction observed in ‘My Green Pet’ (Hwang et al., 2010).

Conducting usability studies with different age groups, such as children to identify their specific needs and interaction patterns to improve Gaia’s design is another aspect that requires improvements. As we continue our development, we aim to not only improve Gaia’s functionality but also deepen the connection it fosters between humans and plants, thereby transforming it from a mere decorative object into a cherished companion.

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