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Master's Thesis
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# Tranquillity at Home: Designing Plant-Mediated Interaction for Better Fatigue Assessment

Keio University
Graduate School of Media Design

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A Master's Thesis
submitted to Keio University Graduate School of Media Design
in partial fulfillment of the requirements for the degree of
Master of Media Design

Michi Kanda

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Abstract of Master's Thesis of Academic Year 2020

# Tranquillity at Home: Designing Plant-Mediated Interaction for Better Fatigue Assessment

Category: Design

## Summary

Our social systems have grown so complex that it is getting increasingly difficult to digest how everyday activities affect our well-being. With growing concerns on mental health and mental fatigue driven by information overload, a parallel discussion has emerged concerning the role of HCI in improving well-being. This thesis follows this paradigm by proposing a bio-digital hybrid interaction system between humans and plants. Its main purpose is to facilitate reflection on subjective well-being by synchronising plant health and eye blink data as a proxy for human fatigue levels. I draw from existing human-plant interaction approaches while integrating physiological sensing technology and slow technology to establish a symbiotic relationship between humans and plants. This work's contributions include: 1) designing a novel means to connect human biosignals with plant health, 2) offering an in-the-wild study of a human-plant synchronisation system, 3) and introducing human-plant interaction for supporting subjective well-being.

Keywords:

human-plant interaction, human-plant synchronisation, bio-digital hybrid systems, slow technology, positive computing

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Hope I can return all your favours one day. Thank you, everyone!

## Chapter 1

# Introduction

> *"Nature itself is the best physician."*
>
> —*Hippocrates*

Figure 1.1 Seeking tranquillity at home: houseplants sales have surged during the COVID-19 crisis [1]

Today we live in a world where many aspects of our lives are suddenly being put on hiatus due to the COVID-19 crisis. The world as we know it has significantly changed and we are forced to re-evaluate our actions, customs, values, etc. while simultaneously struggling to adapt to "the new normal". As a grim outlook and growing insecurity in life further fuel desperation and undermine our ability to think long-term, we are also experiencing a huge spike in mental health issues that could outlast the pandemic. A recent report by the International Committee of the Red Cross reports that one in two people are affected by mental health due to the COVID-19 crisis. In Japan, there has been a 15.4 per cent increase in suicide rates this August from the same period last year. What is more staggering is that the number increase among women and students is overwhelming, amounting to around 40 per cent and 59 per cent, respectively [11, 12]. This trend reflects the reality that our minds are having difficulty catching up with the changes brought by the new normal. Taking care of our psychological well-being has become important and vital more than ever.

As a remedy to cope with stress and anxiety exacerbated by the COVID-19 crisis, there is a growing movement to reconnect with nature. The sales in outdoor sports equipment are experiencing one of the best performances [13]. At the time of this writing, Instagram had 16,300 posts on #covidgardening. This pattern even extends to indoors as well. Patch, an online indoor plant retailer, saw their sales jump to 500% during the lockdown [1]. This surge in demand for houseplants is not surprising when we consider our innate needs to seek connections with nature: Biophilia [14]. As our opportunity to access even nearby nature has become significantly limited due to the widespread social distancing measures and public fear against the pandemic, more people seeking houseplants to fulfil their desire to connect with nature seems an obvious outcome. But there is another reason that we are seeing this increased demand: Plants can bring a positive impact on human health and well-being.

The therapeutic aspect of nature, including houseplants, has been well researched and known [15–17]. This burgeoning demand for houseplants as an emotional comfort not only reaffirms the important role nature plays in human well-being but also opens up an interesting opportunity to explore how we can benefit from everyday interaction with plants to restore our affective health.

Upon delving into this path, there are some challenges that we need to address. First, as plants rarely move on a relatable time scale, it is difficult to discern how plants change each day without some kind of technological assistance (e.g., camera recordings). Further, there is no intuitive way to understand how human interventions can impact plants' growth. Indeed, there are commercially available tools that let you track and monitor plant health such as smart planters and smart gardening system. While these can help people gauge plant health status, they are meant to boost efficiency in managing plants rather than to facilitate human-plant interactions that go beyond watering or adjusting lights. Therefore, our available interactions with plants remain slow and passive. This puts a limitation on how we interact with plants, and by extension, how we experience plants organic changes.

However, slowness can be just as a strong interaction strategy as real-time feedback because slowness has a reflective property in nature. Instead of trying to overcome the temporal difference in actions and reactions (i.e., watering a plant and seeing its growth), we can incorporate slowness into interaction design to facilitate pause and reflection on everyday life. Think of how an hourglass visualises the flow of time. Its gradual movement helps us slow down and calmly digest our experiences with time from a different temporality (i.e., clock time vs organic time) that is richer in experiences. In a similar vein, we can utilise plant growth to reflect on our psychological well-being through interactions that feel organic to us. But how exactly might we achieve such an interaction? This brings us to the main research question of this thesis: How to incorporate plant health into interaction design to support reflection on subjective well-being?

## 1.1. Proposal

As the first step to answer the question mentioned above, this thesis presents a human-plant interaction system that leverages plants' organic growth as a reflective medium. Here, the system offers a novel means to reflect on subjective well-being by synchronising human mental fatigue levels and plant health. In addition to developing a prototype, this research also delves into approaches that

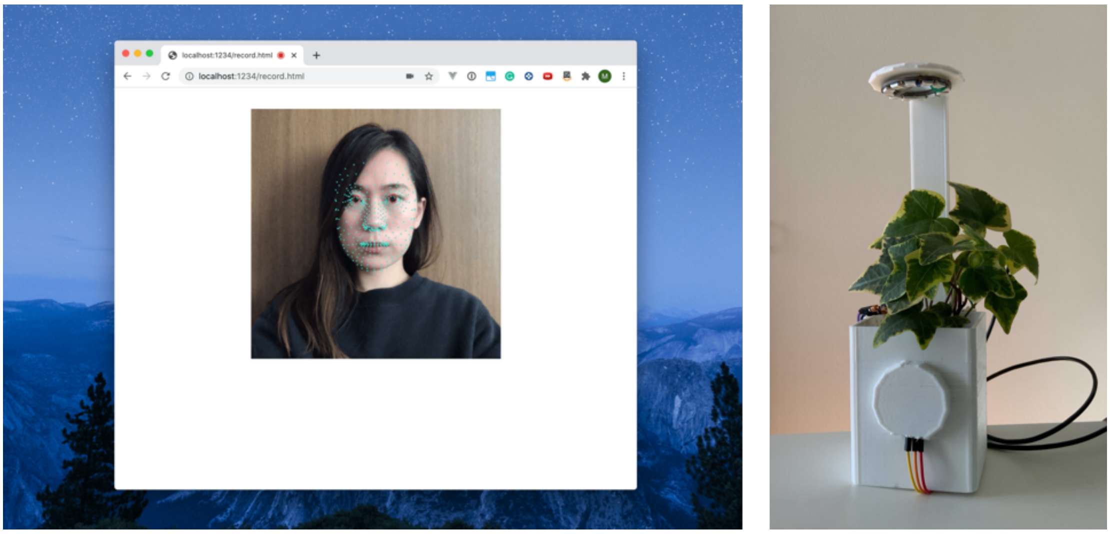

Figure 1.2 Final Prototype. A browser-based eye blink detection system (left) and the augmented plant (right).

best utilise slow interaction for the purpose of improving well-being, visualise the connection between human well-being and plant health, quantification methods for evaluating the effectiveness of such visualisation method, and factors that further advance human-plant synchronisation for enhancing well-being.

In summary, here are the main contributions of this thesis:

- Designed a novel means to connect human biosignals with plant health as well as its visualisation method.
- Presented an in-the-wild evaluation study of a human-plant interaction system, which is still lacking in the majority of human-plant interaction research.
- Provided an evidence on how human-plant synchronisation can help diminish negative affect.
- Offered an alternative to experience human-plant interaction by posing plants

as a medium to induce reflective experience.

## 1.2. Research Question

The prime objective of this thesis is to offer a novel yet familiar means to create an opportunity to reflect on subjective well-being at home through reflective bio-digital hybrid interaction, ultimately aiding in improving subjective well-being. In so doing, this thesis aims to answer the question mentioned above: “How to incorporate plant health into interaction design to support reflection on subjective well-being?”, which requires another line of inquiries:

1) Question 1: How might plants be digitally augmented to support reflective experiences?
2) Question 2: In what ways could reflective human-plant interaction intervene with human affective states? How does such interaction influence how humans perceive the psychological well-being of self and others?

Investigating the first question will be useful in understanding the difference between organic and digital interactions and the possible design space that successfully integrates both interaction methods to build an envisioned user experience. The second question will examine how synchronising human biosignals with plants impacts the perception of subjective well-being; and present a simple and familiar way to observe and reflect on shifts in affective health over time so we can better take care of our psychological well-being.

## 1.3. Thesis Structure

- Chapter 2: I provide a comprehensive overview of relevant concepts, topics, and approaches that cultivates a basis for the envisioned prototype design, which will be introduced in Chapter 3.

- Chapter 3: I describe the concept design and implementation of the human-plant interaction system that I developed to achieve synchronisation of human physiology and that of plants.
- Chapter 4: I present my performed study to evaluate the initial prototype with results and experimentation methods.
- Chapter 5: I conclude this thesis with observations, limitations, and plans for future work that builds upon the study findings described in Chapter 4.

# Chapter 2

# Literature Review

Building a human-plant interaction system for supporting reflection on one's subjective well-being requires an effective strategy to embody human affective states through the bio-digital information translation. In this thesis, I will primarily focus on creating a symbiotic relationship between human affective states and plant physiology to establish the envisioned reflective user experience. This chapter first presents the background on human-plant interaction and then critically reviews the past research on the field and other relevant fields, primarily from a visualisation standpoint. It investigates: 1) the interaction patterns of human-plant interaction, 2) interaction design approaches for reflection, 3) the design space of technologies that measure human biosignals relevant to affective and cognitive states, 4) and finally, the potential approaches for synchronising human physiology with plants.

## 2.1. Hacking Plants for Human-Plant Interaction

Human-plant interaction is a field that studies hybrid interactions between plants and humans through digitally augmenting plants. Its central interest has mainly been about how plants' sensing modalities can be hacked and embodied in HCI. There are two basic augmentation techniques for human-plant interaction: 1) augmentation via sensors and actuators, and 2) augmentation via controlling plants' electrical activities. These two methods are often used in combination. The purpose of augmentation varies from connecting humans with nature and improving well-being [6,18] to automating plant maintenance and monitoring environments [7,19]. The subsequent sections will elaborate on plant augmentation techniques and interaction methodologies more in detail.

### 2.1.1 Plant Augmentation Techniques

Before discussing plant augmentation techniques, we first need to develop an understanding of plants' sensing modalities. Contrary to their calm and inanimate impression, plants can actively engage with the surrounding environment; they can sense the direction of light (a phenomenon known as phototropism), differentiate the colour of light, detect touch (but no pain), respond to sound waves, sense gravity, measure soil humidity and chemicals in the air, and differentiate between cold and heat. While plant sensing modality is limited compared to humans, these unique agencies of plants offer rich interaction possibilities when combined with bio-digital augmentation. Table 2.1 provides an overview of the comparison between human and plant sensing modalities.

As stated previously, human-plant interaction utilises two different augmentation techniques, one with sensors and actuators [20–24] and the other with manipulating plants' electrical activities [2,25,26]. The former extends plants' sensing ability by embedding sensors to their exterior. While this approach promises fairly accurate and stable reading of sensor measurements, and is, therefore, suitable for practical scenarios, it requires as many sensors as your intended sensing mechanisms. On the other hand, the latter allows a light-weight solution to sensing biopotentials. It either acquires plants bio-electrical activities by placing in needle electrodes externally [2,6] or growing conductive wires in vivo [27]. However, the raw bio-electrical signals tend to be small and unstable due to environmental noises; therefore, the system will require a strong amplifier to translate signals to computing devices. In the next section, I will introduce how these augmentation techniques are incorporated into interaction patterns. We will look into them by

| | Human | Plant |
|---|---|---|
| Sight | Respond to a spectrum of 700-400nm<br>Sensed in the retina<br>5 photoreceptors<br>Synchoronises with biological clock | Respond to a spectrum of 750-300nm<br>Sensed in all cells<br>12 photoreceptors<br>Synchronises with the biological clock and seasonal changes |
| Touch | Sensed via touch receptors in skin<br>Responsive to pain, temperature, pressure, friction, and stretch | Sensitive to hot and cold<br>Sensitive to directional pressure (thigmotropism) |
| Hearing | Respond to frequencies from 20Hz to 20,000Hz | Respond to specific frequencies of vibrations |
| Smell | Sensed in the olfactory nerve | Respond to volatile chemicals (e.g. ethylene) |
| Taste | Sensed in the tongue<br>5 taste modalities (sweetness, sourness, saltiness, bitterness, and savoriness) | Sensed in roots<br>Secrete substances below ground to detect nutrients, volatile chemical, or relatives nearby |

Table 2.1 Comparison of human and plant sensory systems

dividing them into the following categories:

- Plant as I/O devices
- Plants for affective communication
- Plants for enhanced nature awareness

### 2.1.2 Plant as I/O Devices

One of the typical embodiment of plant augmentation is plants as I/O devices. Early works in this category explore plant biopotential reactions to various physical stimuli via digital and physical interfaces [25, 26]. Plant Interaction, for example, detects touch sensation through two electrical nodes attached to leaves and visualises electrical activities of a plant caused by human touch in a waveform. Another example that explores human-plant interaction via touch is Botanicus Interacticus. Here, plants are transformed into touch-sensitive control devices by sending a small electric current through a single electrode buried in the soil [2]. With a multiple frequency capacitive sensing technology [28], the system enables a rich gestural experience such as sliding fingers by a branch, detecting which leaves are touched, and measuring user proximity to the augmented plant. These gestural interactions can be programmed to control sound, visual information, and other digital systems. While touch-augmented plants offer a novel tactile user experience, they can potentially stunt plant growth as plants are extremely sensitive to touch; they trigger genetic defence reaction even with the slightest touch [29, 30]. Since plants are also living organisms, and therefore, deserve equal respect just like any other living organisms, non-invasive or minimally invasive approaches should be considered for an optimal symbiotic human-plant relationship.

Other cases employ plant growth as an output device. PlantDisplay [4] synchronises plant growth and digital communication data (e.g., phone calls and email log data) to infer the strength of social ties from plant health status. It controls the amount of water and the light activation time based on the duration of the communication and whom you talk to manipulate plant growth process (e.g., if you frequently talk to your friend, plants grow faster). Biogotchi [3] is also motivated by similar reasoning, but it maps step count from Fitbit data to plant growth instead. The system influences plant growth depends on whether users meet their

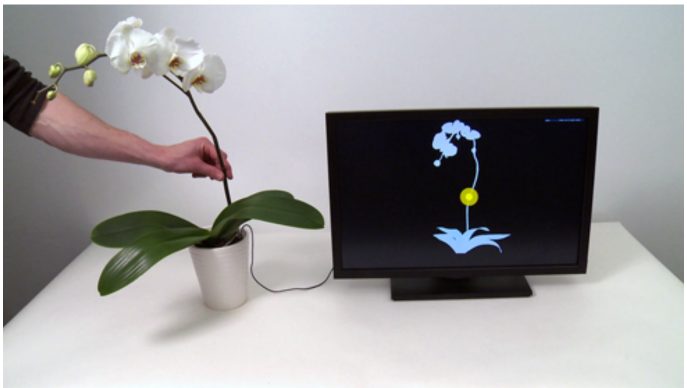

Figure 2.1 Botanicus Interacticus by Disney Research [2]

step count goals. Based on the look of a plant, users can get an abstract sense of their step count performances over time. These examples present plants' potential as informative display as well as insights into how plant physiology and human personal data can be merged as one to improve plant and human well-being all together.

Figure 2.2 PlantDisplay uses plant growth and digital communication data to infer the strength of social ties from plant health status [3]

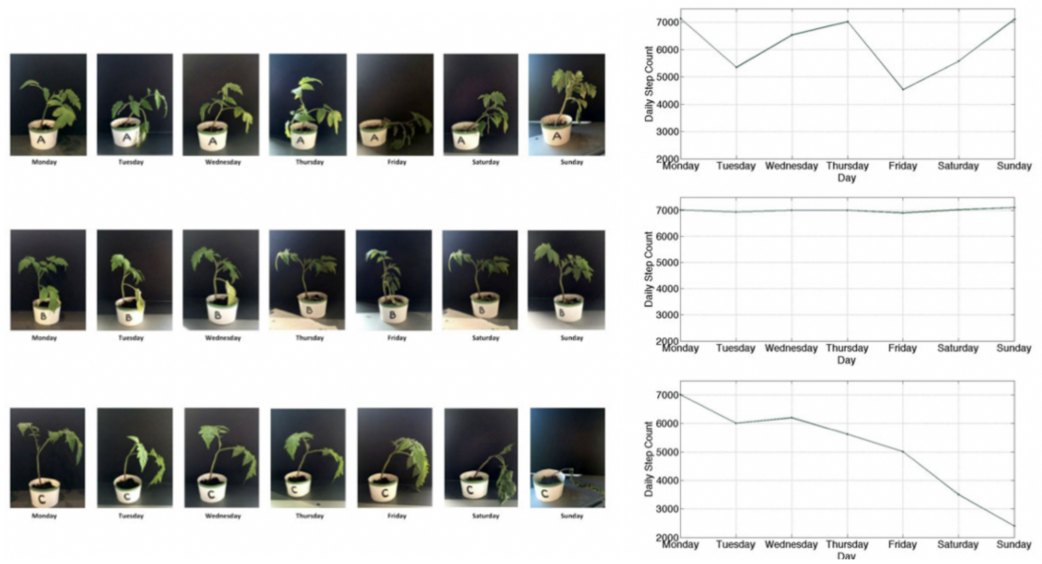

Figure 2.3 Biogochi! maps step count from Fitbit data to plant growth to visualise step count performance) [4]

### 2.1.3 Plants for Affective Communication

Another major design pattern in the human-plant interaction arena focuses on affective communication. It primarily centres around building empathy towards plants [5, 24, 31, 32] or using plants as a medium for enhancing human experience [20, 21]. These two interaction approaches both embed anthropomorphic characteristics to plants, but the major difference between them is that the former is interested in developing better understanding towards plants and the latter aims to provide emotional comfort for humans.

Figure 2.4 Project Florence [5]

An example that represents the former category is Project Florence [5]. It introduces a two-way communication system between plants and humans. Users can send a message to a plant from a Microsoft Surface tablet, and the sentiment and semantics of the message are analysed with Natural Language Processing on a cloud server. After the analysis, the message is converted into a light frequency (i.e., far-red, and blue) that the plant can recognise. The plant then "replies" by printing out its response from a printer connected to itself. This research is a rare example in the human-plant interaction field which exhibits how machine learning can act as a bridge between plants and humans to form affective communication instead of complementing plants' electrical activities for better I/O stabilisation.

There are other examples that focus more on fulfilling human needs. For instance, EmotiPlant presents a use case where augmented plants help elderlies better cope with loneliness [20]. It employs intuitive emoticons visualised via a LED matrix display to communicate plants' supposed emotions when users touch plants. While it does not represent actual plant emotions, it offers insight into how embedding personalities to plants can open up the possibility of plants as active communication companion. In a similar manner, Seo et al. [21] and Tang et al. [22] explore how augmented plants can engage children with autism and elderlies in assisted living. Based primarily on tactile activations and audio-visual interactions, they aim to create a calming effect on human affective states. These studies illustrate a few examples where augmented plants can improve the well-being of vulnerable populations.

Figure 2.5 Affective human-plant communication via emoticons (left), tactile activation and audio-visual interaction (middle and right) [2]

### 2.1.4 Plants for Enhanced Nature Awareness

Using nature as a medium to raise environmental awareness is not new. Sonnengarten, for instance, created a space where users can interact with plants via touch in an urban environment through a media art installation [18]. Its main purpose was to raise awareness of nature by visualising how human interference influenced plants via light feedback.

Kobayashi et al., on the other hand, go beyond human-plant interaction. It proposes a concept called "Human Computer Bioshphere Interaction (HCBI)" which extends the subject of interaction not just to humans and plants but also to animals and the natural ecosystem. It aims to provide a way to connect with nature without causing any environmental damages. Wearable Forest is one example of HCBI interface which connects the sound recordings from a remote forest with an audio-visual interactive clothing system. By bringing natural sounds of wildlife closer to humans in an everyday environment, it heightens a sense of belonging with nature.

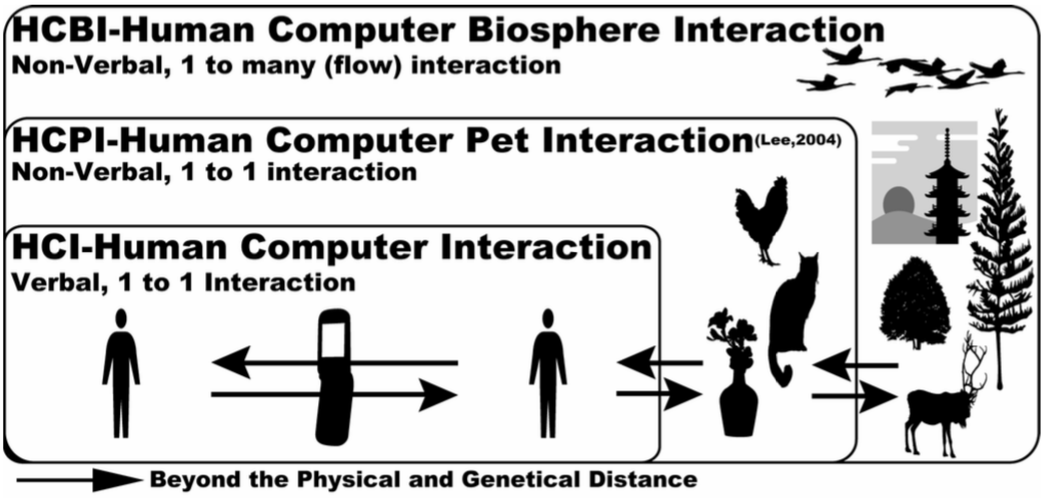

Figure 2.6 Concept diagram for Human Computer Biosphere Interaction [6]

The PLEASED project is another example in this category. However, unlike the previous examples that focus on interactions between humans and plants, it uses plants as biosensors to detect the environmental changes. The project gathered a dataset on plants' reactions to certain stimuli such as flames, chemicals, and electrical signals. This could enable the prediction of these stimuli through a classification algorithm, thereby opening up the possibility of plants as a distributed environment monitoring system.

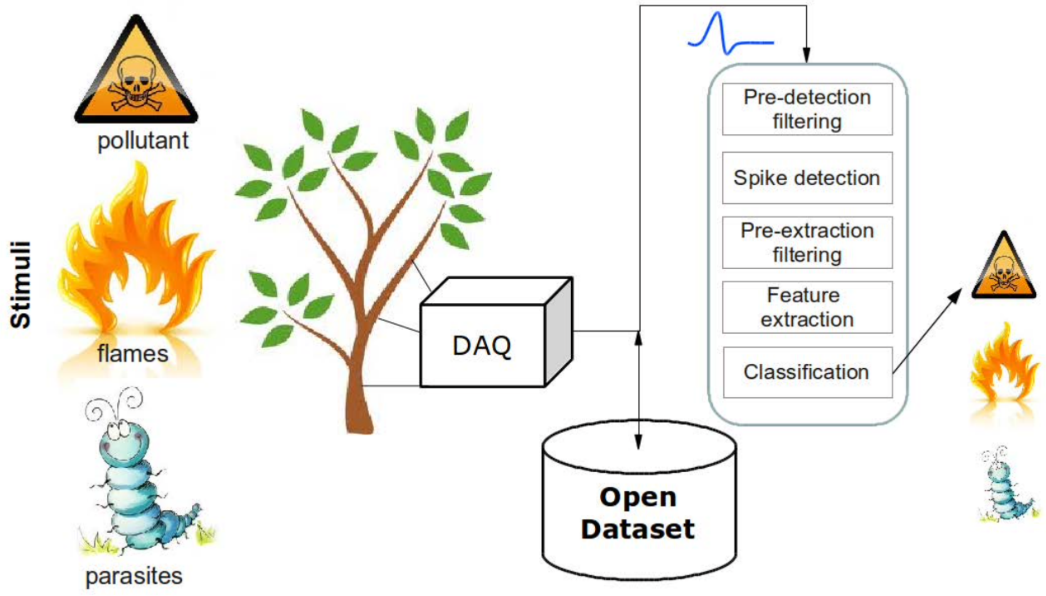

Figure 2.7 PLEASED Project [7]

### 2.1.5 Limitations of the Existing Methods

Many of the works in human-plant interaction offer various alternatives to screen-based interactions. We have seen use cases where plants act as an information display, an active human companion, and an interface to control the digital system. While the approaches in plant augmentation technologies do not vary much (i.e., electrical conductivity sensing), many of the research in this area has illustrated how the same or similar technologies can be extended for various design needs. Yet, there are several challenges that we need to address. First of all, while many have suggested the potential impact of human-plant interaction on raising awareness towards the environment or improving human well-being, very few offer evidence to support such a claim. Another thing to note is that many of the works in human-plant interaction focus on embodying plants' health status or reactions in real-time to promote active engagement with organic life but rarely have explored slowness in plant growth as a medium to induce reflective experiences. Since one of the foci of this thesis is to attract reflection on human affective states, it is indispensable to examine approaches that embrace reflection in interaction design.

## 2.2. Engineering Reflection in Interaction Design

This section will look into how reflective experience can be engineered by examining a series of examples that adopt the Slow Technology philosophy. The philosophy will also provide an ideological backbone of this thesis.

### 2.2.1 Reflection in Slow Technology

Within the domain of HCI, with growing concerns on mental health and information overload driven by ubiquitous computing, a parallel discussion has emerged concerning the role of HCI in improving human psychological well-being. In their seminal work, Slow Technology, Hallnäs and Redström argue that as an increasing number of technologies started to expand beyond the workplace environments, the design of technology should move away from building efficient tools to creating technology for slowness, solitude, and mental rest [33]. The design agenda also includes designing interactive systems that are meant for use across multiple generations. Such a design paradigm offers how slowness can support reflection.

One of the applications that best exemplifies the Slow Technology philosophy is Photobox [8]. It facilitates reflection on past experiences through the photos printed from a wooden box at a random interval each month. The photos are selected from users' Flickr albums. The intention behind this concept was to allow re-interpretation of past life events by giving a physical form to the digital photos. Of course, photos are not the only medium for reflection. Olly offers a physical medium to re-engage and re-experience digital music [9]. It features a wooden disc inside which users need to spin it whenever they want to listen to a song. The songs are selected based on users' music listening history. One particularly interesting characteristic of Olly is that the speed of the disc rotation is linked to how long ago the song was played. It is an intriguing embodiment of reflective experience that allows users to experience temporality through physical action. While these examples do not incorporate plants in the interaction, they offer valuable insight into how digital data can be re-materialised to promote reflection.

Figure 2.8 Photobox [8]

Figure 2.9 Olly [9]

## 2.3. Inferring Human Affective States from Biosignals

As stated in the introduction, the ultimate goal of this thesis to aid in improving psychological well-being through reflective experience. Since stress is one of the biggest factors that exacerbate human affective health, this review will examine existing research on sensing technologies that attempt to infer stress levels from biosignals. This includes: 1) eye movement detection, 2) heart-rate variability, 3) and galvanic skin response. Also, since the envisioned interaction for the prototype is set in a real-world setting and requires sensors to be installed to plants, I will primarily discuss mobile biosignal sensors with consideration for practicality.

### 2.3.1 Biosignals Related to Stress

There are mainly two types of biosignals: 1) physical signals, 2) and physiological signals. The former involves measures of physically observable changes such as pupil dilation, blinks, and facial expressions. The examples of the latter signals include heart rate (Electrocardiogram or ECG), brain activities (Electroencephalography or EEG), and the electrical potential difference between the retina and cornea (Electrooculography or EOG). By observing these biosignals, we can infer the level of stress. I will examine low-cost, unobtrusive biosignal sensing technologies that could be easily introduced to real-life scenarios in subsequent sections. As the envisioned prototype requires practicality for home uses without needing to wear it when sensing takes place, any technologies that are obtrusive and impractical are outside of the scope of this review.

### 2.3.2 Stress Assessment Technologies

One of the most promising technologies that meet the aforementioned prototype criteria is EOG. When there are eye movements, it measures the electrical potential difference between the retina (-) and cornea (+) through electrodes placed on users' forehead around the eyes. This enables detecting eye blinks without any recording devices. While the EOG measurements are not as accurate as conventional eye-tracking technologies (e.g., pupil detection), they offer a low-power solution to monitoring eye blinks.

The significance of eye blink detection is that eye blinks can indicate mental fatigue levels [34]. A smart eyewear, J!NS MEME, is a practical example of this. Since it is lightweight and can easily be integrated into other computing devices via Bluetooth, this makes it an ideal candidate for this thesis.

Another possible candidate that is capable of measuring eye blinks is digital image processing. It incorporates a face landmarks detection algorithm to pinpoint the location of face features. In particular, TensorFlow's face landmarks detection libraries offers a real-time browser-based solution with high accuracy. It can predict 486 3D facial landmarks to infer the approximate surface geometry of a human face. While J!NS MEME is more straightforward to use and requires less computing power, a browser-based eye blink detection is more unobtrusive since it can measure eye blinks from users' familiar settings (i.e., a desk and laptop) without asking users to get used to a new device just to measure eye blinks.

Figure 2.10 EOG-enabled smart eyewear, J!NS MEME

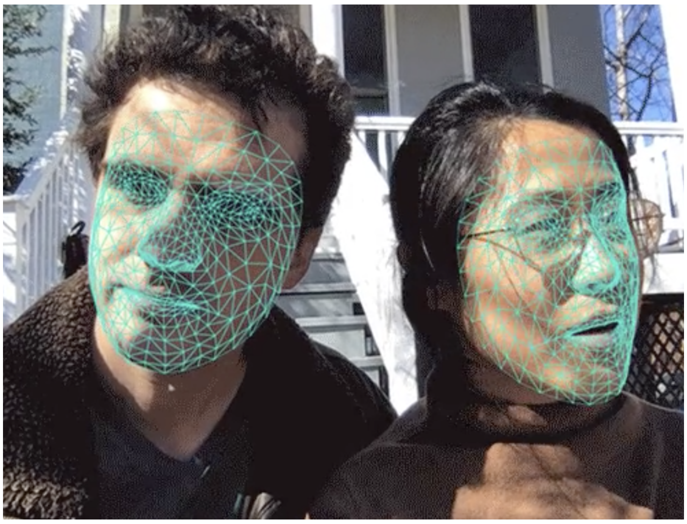

Figure 2.11 Face landmarks detection by TensorFlow.js

Other examples of practical and unobtrusive applications of mental fatigue assessment in the wild are pulse and skin conductance sensors. The former can be used to analyse fatigue by monitoring heart rate variability (HRV) while the latter measures fatigue based on a change in the electrical properties of skin flowing through the two electrodes. While these physiological sensing technologies offer an off-the-shelf solution to fatigue assessment, they require users to wear the devices in order to measure and collect relevant data. Since I envisioned the user experience for my prototype to be minimally unobtrusive and easy to be integrated into users' daily routines, a physical signal sensing that does not require any additional equipment for biosignal tracking appear to be an ideal option.

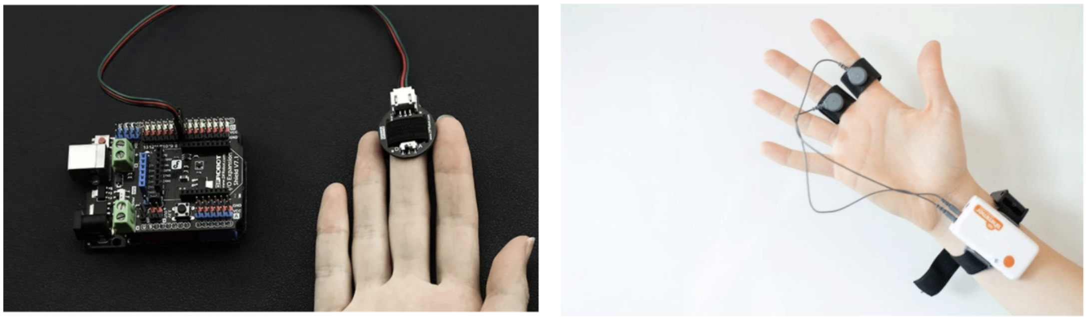

Figure 2.12 Applications that use pulse sensors (left) and skin conductance technology (right)

## 2.4. Synchronising Human Biosignals and Plant Physiology

Given the variety of interests in bio-digital hybrid solutions within the current design space for human-plant interaction, a concept of human-plan symbiosis through utilising personal data offers an interesting perspective in this domain. Yet, existing applications are limited to fitness tracking, stock price tracking, and plant management system. I believe that extending human-plant synchronisation that incorporates human biosignals and plant health can not only boost the therapeutic value of plants but also better care for one's subjective well-being.

# Chapter 3

# Design

Due to the prolonged social distancing measures and fear of the COVID-19, people across the world are increasingly spending a significant amount of time at home during the pandemic. This imposed restriction has inevitably deprived many of one's agency, putting a considerable strain on mental health. As a way to combat growing concerns about deteriorating mental health, this thesis aims to devise a system to reconnect with nature at home through plants. Introducing live plants to interiors can potentially improve well-being [16, 17] not to mention an additional value of having a great companion to a sedentary lifestyle. In this research, I propose a human-plant interaction system that helps observe daily mental fatigue levels by enabling the synchronisation of human fatigue levels with plant health to accommodate this increased need for tranquillity at home.

As mentioned in Chapter 2, there has been little attempts to embrace plants' organic growth as a medium for inducing reflection on psychological well-being. Only a few have considered incorporating personal digital data into human-plant interaction to promote well-being [4]. Further, while there is a variety of technologies to measure biosignals for gauging mental fatigue levels, the examples that successfully integrate such technologies into human-plant interaction systems are close to none.

In this chapter, I will address these issues through my prototype design. I will first explain the concept behind building the prototype, design process, implementation, and possible application scenarios.

## 3.1. Prototype Concept

### 3.1.1 Plant as a Reflection of the Human Mind

The goal of designing the prototype is threefold: 1) to synchronise plant health with human biosignals (i.e. eye blink data), 2) provide an intuitive interface to assess one's daily mental fatigue levels over time, 3) and facilitate reflection on personal affective states.

A number of factors would need to be considered upon designing the prototype. First, since the organic time frame dictates plant growth, there is a time delay between input and output in the interaction process; one cannot easily connect an intervention with its resulting feedback. This poses a certain challenge on using plants as information displays; therefore, we need another form of interface to complement this shortcoming. Another factor to consider is how multiple temporalities (i.e., organic vs. human perception of temporality) influence interaction opportunities. Further, we need to ensure human mental fatigue levels and plant health remain in sync because it influences its overall user experience in the long run. I will cover each factor in the following sections.

### 3.1.2 Requirements

The success of this prototype largely depends on how well the bio-digital hybrid system communicates the connection between plant health and mental fatigue levels. The system needs to have features that allow users to infer and evaluate their mental fatigue levels intuitively so that plant health can function as a proxy for human mental fatigue levels.

As for data visualisations, imparting a sense of the symbiotic relationship between plant health and subjective mental fatigue levels is indispensable in achieving a seamless user experience. Therefore, changes in mental fatigue levels need to be communicated through an augmented plant instead of digital screens. Also, since the system visualises the information through an augmented plant, the system should be able to communicate the data in a meaningful way without relying on text-based information. Further, since the envisioned user experience is to induce reflection over a specific period (i.e., each day and week), the visualisations should account for multiple temporalities so that users can compare and assess changes in their affective states over time.

Lastly, to measure mental fatigue levels without enforcing sudden behavioural and environmental changes, the system will be installed in an everyday environment (e.g., a desk at home). As the prototype is expected to be in use while users are engaged with daily activities, the interaction should demand as minimal attention as possible.

When these requirements are successfully met, users will be encouraged to improve their affective states because plants' well-being depends on mental fatigue levels.

## 3.2. Implementation

### 3.2.1 Setup

The prototype is comprised of following components: 1) an augmented plant with sensors and actuators for monitoring and visualising plant health, 2) a grow light (LED) to regulate plant growth, 3) software for computing human fatigue levels based on daily eye blink data, 4) a Wi-Fi integrated development board to communicate the data between the software and the plant.

Here is the entire list of the system setup:

- Living Plant
- ESP-WROOM-02 Wi-Fi development board with an Arduino functionality
- Grow LEDs for controlling plant growth and visualising mental fatigue levels

Figure 3.1 Prototype components

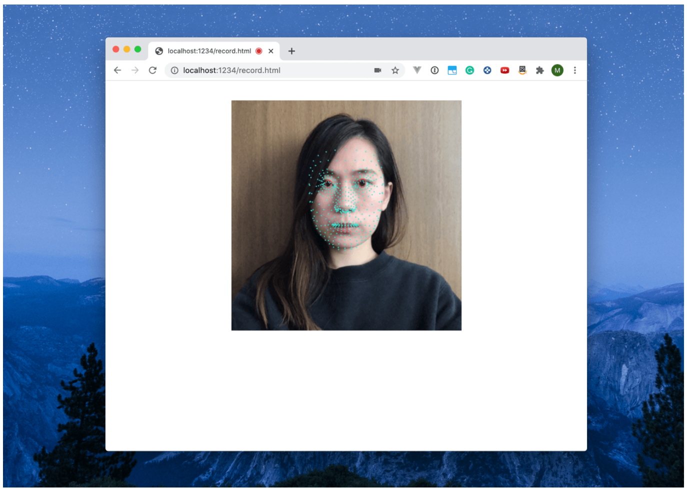

Figure 3.2 Browser-based eye blink detection software using TensorFlow's facial landmarks detection library

- LEDs for visualising plant health
- LDR (Light Dependent Resistor) sensor for measuring the intensity of the grow light
- Temperature and humidity sensor to monitor plant health
- Eye blink detection software program using the face landmarks detection library from TensorFlow.js, Node.js, and MongoDB

### 3.2.2 Measuring and Visualising Mental Fatigue

The key part of this prototype involves effectively measuring and visualising mental fatigue levels. To achieve this, a reliable biosignal sensing method and intuitive visual feedback are necessary (the former supports measuring mental fatigue levels while the latter provides a visual cue for assessing them).

For measuring mental fatigue levels, I built an eye blink detection system using face landmarks detection library from TensorFlow.js. Since the TensorFlow library does not offer a feature for computing eye blinks, I applied the algorithm proposed by Soukupová and Čech. The system is capable of measuring and counting eye blinks in real-time webcam video streams. The detection method is based on machine learning classification, which utilises a metric called the eye aspect ratio (EAR) [10]. Upon performing its classification tasks, the algorithm computes the absolute distance between each set of vertical eye landmarks (the difference between P2 and P6, P3 and P5 in Figure 3.3) and divide the sum of each vertical distance by the multiple of 2 of the absolute distance of horizontal eye landmarks (P1 and P4 in Figure 3.3). The equation for the eye aspect ratio is as follows:

$$EAR = \frac{||p2 - p6|| + ||p3 - p5||}{2||p1 - p4||}$$

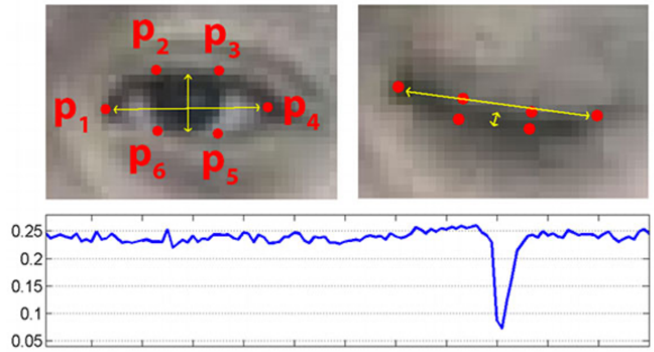

Figure 3.3 Implementation of eye aspect ratio based blink detection [10]

As for visualising mental fatigue levels on an augmented plant, there are several key criteria I considered. First, since I envisioned the prototype as an intuitive ambient display that requires minimal attention, the feedback needed to be primarily based on visual feedback rather than text-based feedback. Also, to create a cohesive impression of time between plant and human temporalities, and to build reflective user experience, effective use of time delay in the visual feedback is required. I describe the mechanism of the visualisation decisions I employed below:

- Users' daily eye blink data is collected from the web application, which then is translated into daily mental fatigue levels.
- At the end of each day, the augmented plant visualises users' daily mental fatigue levels via the grow LED installed on top of the planter.
- The grow LED signifies user mental fatigue levels in two colour variations: 1) purple (a combination of far-red and blue) for good performance, and 2) blue increased fatigue levels.

The threshold for determining user mental fatigue levels was set to 15 blinks per minute since it has been reported as normal spontaneous eye blink rate [35]. An average eye blink rate per minute equal to or higher than 15 indicates fatigue. Based on this threshold, the colour of the grow LED is set; when the user's minute average eye blink for the day is greater than 15, the grow LED turns to blue; when the minute average is equal to or below 15, the grow LED turns to purple. The significance of these colour variations will be elaborated in the next section.

### 3.2.3 Manipulating and Visualising Plant Health

Visualising plant health is another crucial ingredient to create a sense of synchronicity between human mental state and plant health. To determine a means of assessing plant health, I primarily considered two sensing modalities; soil moisture sensing and light sensing. Touch sensing was not part of this consideration since it causes unnecessary stress to the plant, potentially stunting plant growth.

After conducting a two-week study of these two sensors' readings, I chose an LDR sensor as a primary source of assessing plant health. Due to the seasonal reason at the time of this study, soil moisture level stayed mostly consistent throughout the duration, whereas there were noticeable fluctuations in light levels.

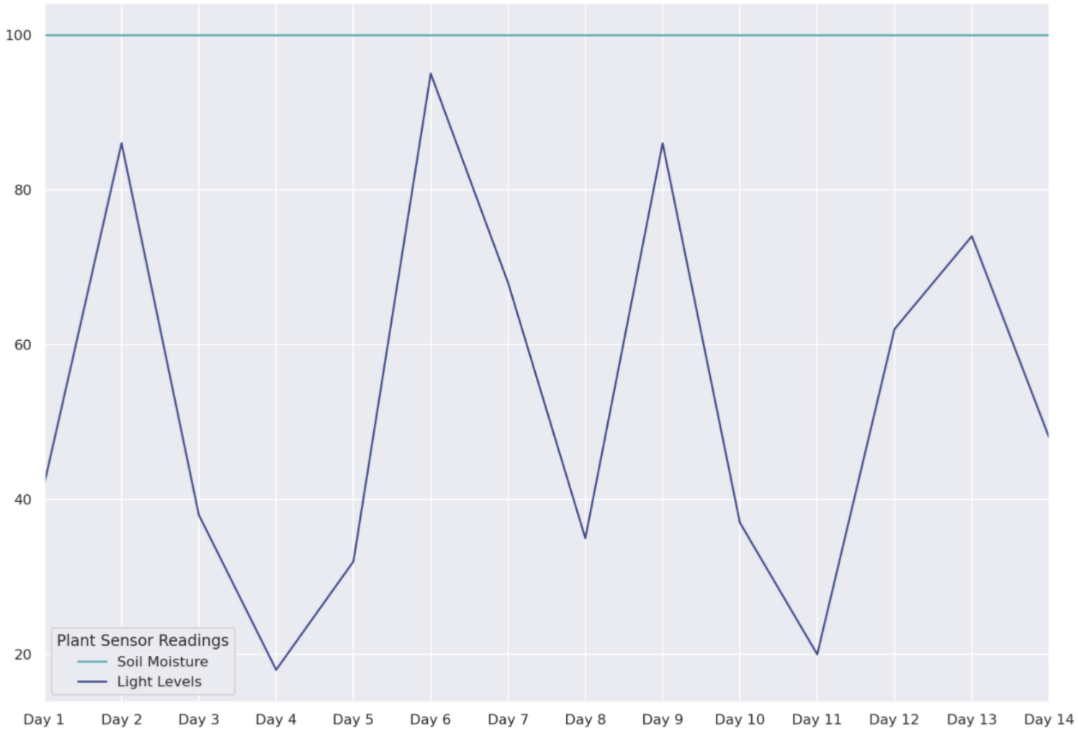

Figure 3.4 Comparison of light and soil moisture sensor readings. Light levels showed much more fluctuations while soil moisture levels stayed consistent over the two weeks test period.

An LDR sensor was later integrated into the augmented plant to detect the light intensity of the grow LED. Its reading was then converted into three variations of colours through the LEDs (serves as a plant health indicator) placed in front of the planter (see Figure 3.4). These colours represent the plant health status (Green=healthy, Yellow=wilting, and Red=needs attention). Since LDR sensors are sensitive to other light sources, which could potentially activate the plant health indicator without the input from the grow LED, the light level reading was activated only in the following conditions: 1) during the hours that room lighting provides consistent brightness (e.g. evening), 2) when there is a sufficient amount of eye blink data to compute an eye blink minute frequency. The light level reading was also adjusted based on an eye blink frequency. In addition, I incorporated a temperature and humidity sensor as a secondary source of assessing plant health. While the colours of the LEDs that indicate plant health do not directly correlate with actual plant health, it will provide useful information on plant health to users.

### 3.2.4 Interaction Design

The basic interaction flow is as illustrated in Figure 3.5. The eye blink detection application collects users' eye blink data from their laptops during the day. At the end of the day, the software computes the eye blink average for the day and sends the value to Arduino via Wi-Fi. The colour of the grow LED is set based on the eye blink rate. When the grow LED is turned on, the plant indicator LED also turns on accordingly. While determining plant health is based on proxy data, the system still offers a novel opportunity for users to objectively assess their own mental fatigue levels by synchronising human mental fatigue levels with plant health.

The complete interaction logic on how the grow LED, an LDR sensor, and the plant health indicator function as a whole is listed below:

Figure 3.5 Prototype with LEDs activated. These colours represent the plant health status (Green=healthy, Yellow=wilting, and Red=needs attention)

- The two colours of the grow LED either induces (purple) or suppresses (blue) plant growth.
- The LDR sensor reads the light intensity from the grow LED. Based on this reading, the colour of plant health indicator is determined.
- When the grow LED colour is purple, the plant health indicator LED turns to green, signifying good health status.
- When it's blue, the plant health indicator LED turns to yellow, signifying mild deterioration in its health status.
- Lastly, when its light intensity is below a certain light level threshold, the plant health indicator turns to read, demanding user attention.

This logic connects human mental fatigue levels with plant health through the feedback loop among users, the grow LED, and plant health indicator. Since the colour of the grow LED is synced with the user's mental fatigue levels–therefore, the future of plant's health depends on the user's mental state–it creates a motivation to pay attention to one's affective health. Also, delaying the light feedback until later in the evening is intended for creating enough time to reflect on one's mental state objectively. In short, by showing the direct link between human fatigue levels and plant health, the system offers a means to reflect on one's subjective well-being and aims to show how plants and human well-being can improve together as a result of human-plant synchronisation.

In the next chapter, I will evaluate the extent to which this human-plant synchronisation approach positively or negatively influences human subjective well-being.

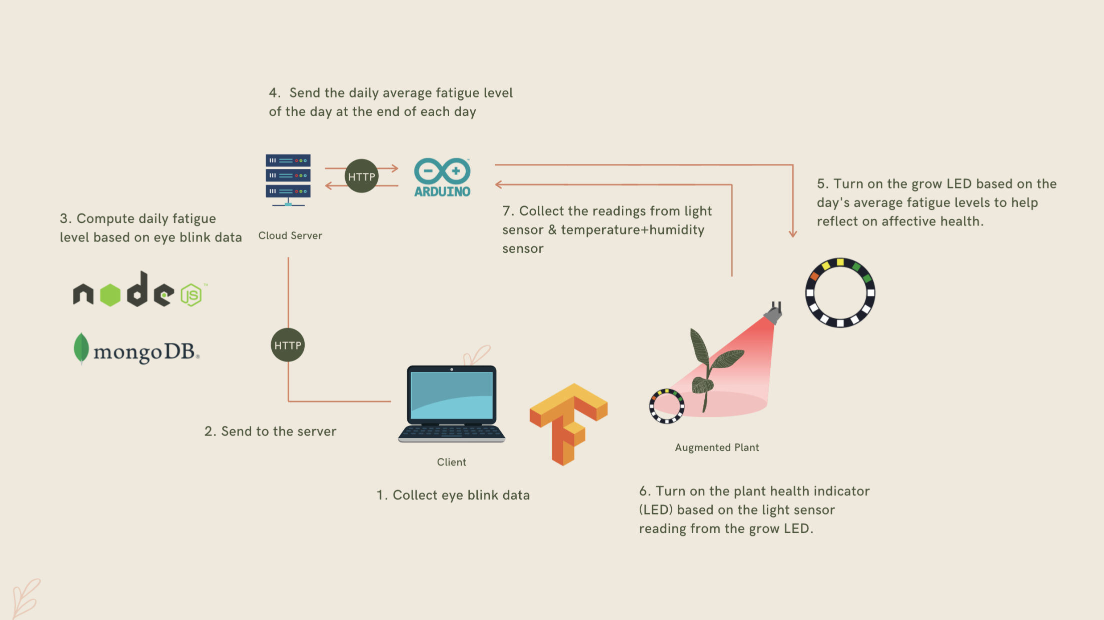

Figure 3.6 System architecture with interaction flow

## 3.3. Application Scenarios

In this section, following possible application scenarios for the envisioned concept are discussed.

- Monitoring mental health at work
- Monitoring mental health for the elderly
- Remote check in system for families and friends living apart

### 3.3.1 Monitoring Mental Health at Work

One possible use case for this prototype is for working professionals with desk-based jobs. For many of us, work consumes the major part of daily lives. Yet, the majority of people reports low satisfaction at work. According to the survey by Recruit, Inc., the percentage of Japanese working professionals who were satisfied with their job was 39.9% in 2018 [36]. The poll by Randstad Workmonitor in 2020 also reported that Japan ranked the lowest in job satisfaction out of 34 countries surveyed [37]. While there is a variety of elements that can contribute to low job satisfaction level, the importance of better mental health care should be of utmost priority at work since job satisfaction level is related to the mental health of workers [38]. Yet, many companies struggle to monitor employees' mental health in a timely and unobtrusive manner. Allowing individual workers to observe their fatigue levels through plants instead of formal assessment methods can offer a user experience that feels much less like an assessment.

### 3.3.2 Monitoring Mental Health for the Elderly

While the primary application scenario is for individual use, the prototype can also offer benefit to multiple user interactions, especially for those who require extra attention to affective health. One important application of this scenario is for the elderly in assisted living or living alone. Loneliness and alienation among the elderly have become one of the urgent social issues our modern society is experiencing. Nearly 30% of all seniors live by themselves, according to the U.S. Census Bureau [39]. In Japan, 1 in 8 male elderly lives alone while 1 in 5 female elderly live alone [40]. The prototype can offer a means for such a vulnerable population to communicate their mental state to their caretakers. While the prototype is intended for mobile devices with cameras, the core concept is still feasible with a camera module attached to an Arduino board.

### 3.3.3 Remote Check In System for Families and Friends Living Apart

Another interesting application for the prototype would be a remote communication system between families and friends. Due to the COVID-19 crisis, it has become increasingly challenging to remain in touch with our loved ones. So-called

"Zoom fatigue" is prevalent as many rely on virtual platforms for daily communications [41]. When placed in between homes, this prototype can offer a means to monitor other's mental state, providing a daily piece of mind for families and friends. Also, since the prototype does not require any technology literacy to use, it can be used across generations.

# Chapter 4

# Validation

This chapter elaborates on a ten-day in the wild evaluation study with four individuals. It covers the prototype validation process, study findings, discussions, and methods. The purpose of this study was to conduct both quantitative and qualitative evaluations on how synchronising plant health and human fatigue levels influences overall subjective well-being. The findings from this study also provided insights for the next iteration of the prototype. Upon conducting the study, I posed the following questions:

1) How does synchronising human fatigue levels with plant health affect users' subjective well-being? Does such a feedback loop result in an increase in negative/positive affect? If so, why?

2) What are the possible long-term impact of human-plant synchronisation on both humans and plants?

The first question investigates the implications of placing the direct responsibility of taking care of plants' well-being on humans. As plant health depends on users' degree of fatigue each day, there is a possibility that the implemented form of human-plant synchronisation could unnecessarily increase users' stress instead of easing it. On the other hand, it can also help users re-examine their daily activities so that they can make conscious effort to change for the better or feel less stress even when they cannot avoid stress-inducing activities. Therefore, we must build a better understanding of how users feel and react to human-plant synchronisation as a form of intervention so we can minimise the adverse side effects proactively and support cultivating human well-being.

The question about the long-term impact of human-plant synchronisation derives from the fact that the research on this field is virtually non-existent. While there is a well-documented list of research on therapeutic benefits of having nature in your surroundings as well as research on digital augmentation of plant physiology, the research that effectively combines these two aspects and provides long-term studies on the impact of human-plant synchronisation are scarce. Together with a long-term study, we will gain insights on achieving a symbiotic relationship between humans and plants for better affective health.

## 4.1. Results

The study was conducted at each home of the study participants with their laptops for ten days. Six volunteers were recruited for this study. Two of them opted out after the fifth day of the study due to their schedule conflicts. There were two parts to the study setup: 1) a web application which records participants' eye blink data from a web camera in real-time, and 2) a digitally augmented plant. The former is for assessing participants' mental fatigue levels, and the latter is to monitor plant health as well as to communicate daily fatigue levels of each participant. The participants were provided with an ivy plant which they placed within the peripheral distance. Prior to the study, they were given a pre-study survey to assess their chronic fatigue levels and subjective well-being from last week. At the end of the study, they answered a post-study survey to re-assess the same criteria asked in the pre-study survey for comparison. For user tasks, each participant was instructed to record their eye blink data during the day together with psychomotor vigilance tests (PVT) to assess their fatigue levels. They were also given surveys to evaluate their subjective well-being and the degree of synchronisation with their plants at the end of each day. I report both aggregated results and detailed results in the following sections.

### 4.1.1 The Impact of Human-Plant Synchronisation on Subjective Well-Being

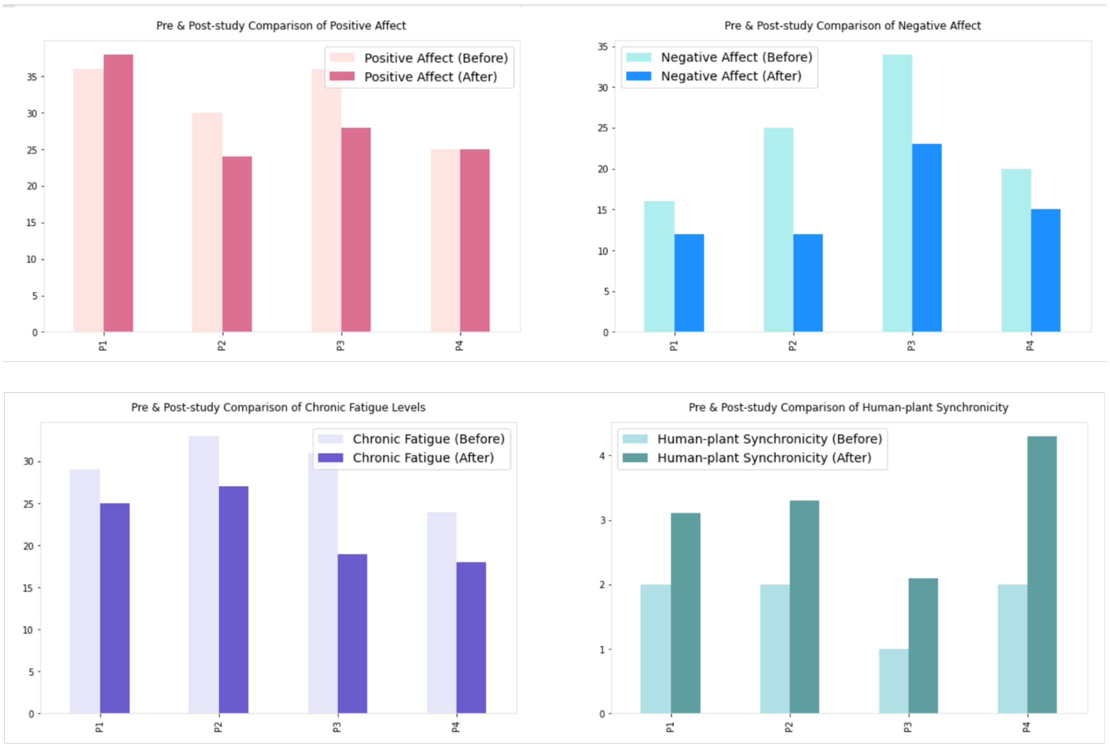

Figure 4.1 Comparisons between the pre-study and post-study data on positive affect, negative affect, and chronic fatigue level ordered from left to right.

Figure 4.1 shows a summary of the pre-study and post-study analysis of subjective well-being and chronic fatigue levels. While positive affect remained more or less the same, all of the participants experienced a decrease in both negative affect scores and chronic fatigue levels. The mean score for the weekly positive affect was 28.75 down from 31.75 in the pre-study while that of the weekly negative affect shifted from 23.75 to 15.5 in the pre-study (the maximum score for both positive and negative affects is 50). The mean chronic fatigue levels went down by 6.75 points from 29 (the total score ranges from 10 to 50, and scores above 21 indicating fatigue). Although most participants' fatigue levels remained mildly high, a significant decrease in both negative affect and chronic fatigue levels even without much discernible changes in positive affect shows a promising sign that human-plant synchronisation could effectively help improve subjective well-being. However, since the study was done in the wild, measuring the degree to which the study influenced the participants' subjective well-being remains a challenge.

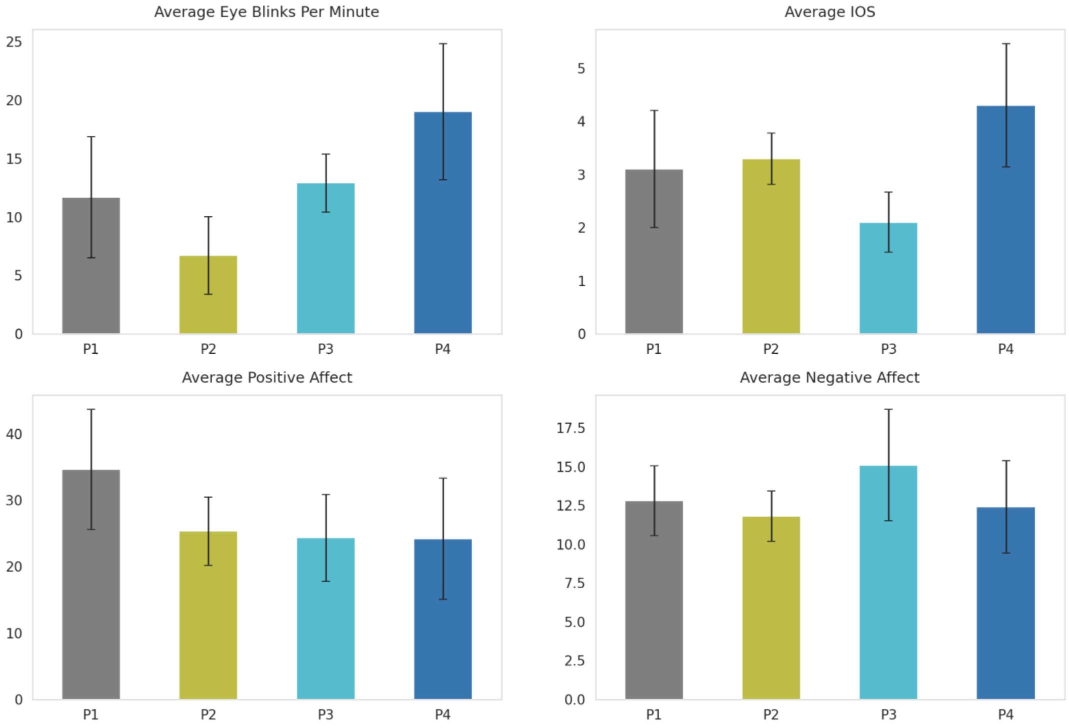

Figure 4.2 10-day average of minute eye blink frequency, human-plant synchronicity levels (IOS), and positive and negative affect for each participant.

On average, the participants had 13 blinks per minute, the frequency ranging from 3 to 27. So their average fatigue level assessed from the eye blink data remained below the threshold. However, since their reported mean chronic fatigue levels still indicated fatigue, the eye blink frequency threshold may need to be re-adjusted. The potential inaccuracy in the eye blink detection application is a possibility yet appears small. Three participants agreed that the system represented their fatigue level accurately (rated 4 out of the 5-point Likert Scale) while one participant disagreed (rated 2). Figure 4.3 offers detailed analyses of each participant's data on minute eye blink frequency, subjective well-being scores (PANAS), and human-plant synchronicity levels (IOS) over the ten days period.

The correlation analysis of average eye blinks per minute, positive affect, negative affect, and human-plant synchronicity levels (Figure 4.4) revealed a strong inverse correlation between negative affect and human-plant synchronicity levels (r=-0.8). This suggests that the higher the sense of human-plant synchronicity, the less the participants' experienced negative affect will be. However, the degree of human-plant synchronicity had no statistically significant impact on positive affect (r=0.02). There was also a positive correlation between eye blink frequency (fatigue levels) and human-plant synchronicity levels (r=0.5). The r-value was higher among individuals who have regular interactions with plants even prior to the study (r=0.8), suggesting that the participants felt a stronger connection to their plants when their fatigue levels were high. This result aligns with the post-study survey data where three participants reported feeling a strong sense of connection to their plants when they experienced high fatigue levels.

- *"When I pulled an all-nighter last Saturday to finish a presentation, having formed a connection with the plant over the previous days, I felt I had a little company with me as I was working through the night. It was a nice feeling." (P1)*

- *"I felt exhausted on Day 2 of the study, and I felt it even before the plant lit up. After the light up, the yellow light reflected my condition's tiredness*

Figure 4.3 Analyses of each participant’s changes in PANAS and IOS

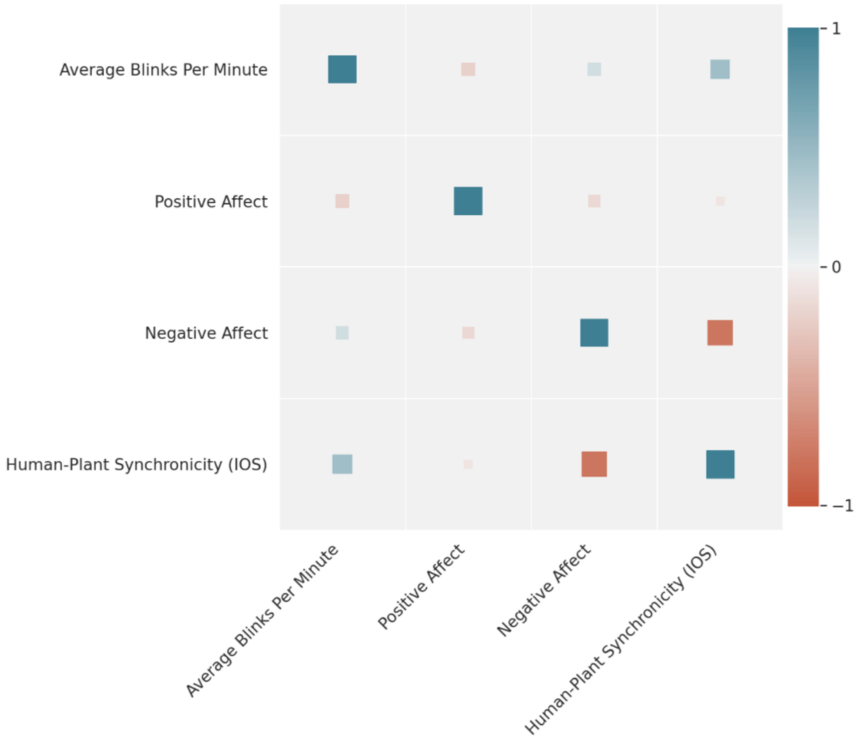

Figure 4.4 Macro analysis of correlations among eye blink frequency, subjective well-being scores (PANAS), and the degree of human-plant synchronisation (IOS).

*level that day. This was the moment when I felt strongly connected to the plant." (P3)*

- *"When I was feeling exhausted and the plant LED was also red, I felt the most strong connection." (P4)*

In sum, it appears that while there was a minuscule impact on improving positive affect, the degree to which people form a connection with plants plays an integral role in reducing negative affect and chronic fatigue levels. Since negative affect is positively related to depressive symptoms and reduced cognitive performances [42], this finding strengthens the importance of engineering human-plant synchronisation.

## 4.2. Discussion

### 4.2.1 Study Question 1

Based on the research findings, I have shown how synchronising human fatigue levels with plant health could help reduce negative affect. This finding not only confirms the existing research evidence on the therapeutic benefits of active interactions with houseplants but also offers insight and a means to engineer human-plant synchronisation for better fatigue assessment.

When asked about how they see the impact of the augmented plant on their subjective well-being, all of the participants acknowledged that it would enhance their subjective well-being (Q5). In addition, their overall experience with the human-plant synchronisation was positive. Two people rated 4, and the rest rated 3 and 5 respectively out of the 5-point Likert Scale. Prior to the study, there was a concern that placing the responsibility of taking care of plants' well-being on humans may cause unnecessary psychological pressure. However, none of the participants was bothered by the visual feedback loop from the augmented plant even though some of them felt relatively high pressure of having responsibility over their plants (Q4 and Q2). The pressure did not seem to affect their opinions on the impact of the human-plant synchronisation on their subjective well-being as well. Despite the pressure, the participants saw having a stronger connection to their plants as an important step for improving their subjective well-being (Q7 and Q9).

Some participants expressed confusion when they felt a gap in their subjective fatigue of the day and the plant health indicator. While the extent to which it influenced the participants' subjective well-being requires further examinations, minimising this discrepancy is vital to ensure a high degree of human-plant synchronicity and low negative affect. To this end, we need the data on subjective fatigue levels to better represent users' fatigue levels in addition to the fatigue assessment from eye blink data.

To summarise, while the participants considered that human-plant synchronisation would benefit their subjective well-being, ensuring a high degree of connection to the plants will be challenging without any means to close the gap between subjective and objective fatigue levels.

### 4.2.2 Study Question 2

Perhaps as equally, if not more, important as evaluating the impact of the human-plant synchronisation system on human subjective well-being is assessing its long-term implications. Based on the post-study observation, we found out that the synchronisation of fatigue levels with plant health helped the participants better evaluate their fatigue levels (Q3).

Here are some of the user feedback gathered from the survey:

- *"I didn't expect the plant would lead me to reflect on my fatigue levels on a daily basis. It seemed to provide a measure for me to assess how my day had went, every day. If anything, it definitely brought my stress and fatigue* *levels to my attention." (P1)*

- *"I look forward to the time the lights turn on. I feel it's easy to form a habit of reflection with the prototype." (P4)*

Introducing the augmented plant as a reflective medium seems to support the participants' daily reflection habit to a certain degree. While the participants were reminded of the time the plant LEDs will light up for the first few days, they were not encouraged to set aside a time for self-reflection. Observing the plant LEDs at the end of the day seems to offer structure to their lifestyle. The unobtrusiveness of the prototype also appears to contribute to this aspect. However, it is important to note that since the participants were asked to rate their subjective well-being at the end of each day, this may have facilitated self-reflection habit.

As for the long-term implications on plants, since the study was conducted during winter and thus plants required much less watering, it is difficult to fully assess how human-plant synchronisation may have influenced plants. The average daily light levels, temperature, and humidity in every room were ensured to stay consistent to eliminate external impact factors as much as possible. However, we will need to compare the changes in plants in both controlled and experiment settings to confirm that human well-being and plant well-being can achieve symbiosis. Further, a seasonal study will be necessary as we can expect habit changes in different seasons as well as the environmental changes in and around plants.

Nevertheless, while the study only lasted for ten days, it still offers insight into how human-plant synchronisation can help facilitate forming a regular reflection habit in addition to aiding in better evaluation of their fatigue levels.

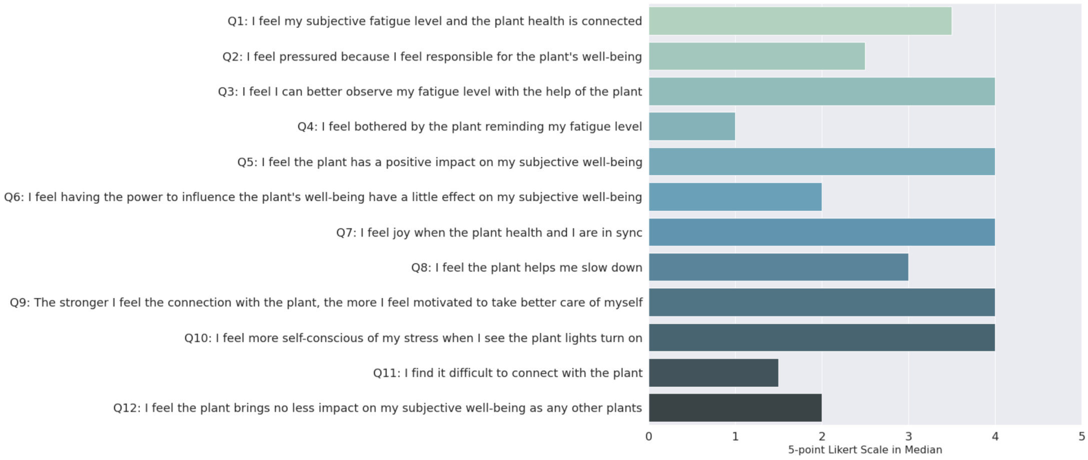

Figure 4.5 The questionnaire result in Likert Scale with median

## 4.3. Methods

### 4.3.1 Participants

The data was collected from four participants recruited from Keio Media Design. The age ranged between 30 and 36 (mean=29.7) with two females and two males. Each was compensated with 1500 yen at the end of the study. The participants had different degrees of experience with plants, ranging from no experience to regular interaction. Regardless of their experience with plants, their emotional connection to plants appears to be low (mean=1.75, rated in 7-point scale). In addition, their pre-study weekly subjective well-being score was 31.75 out of 50 for positive affect and 23.75 out of 50 for negative affect. Their chronic fatigue levels ranged between 24 and 31 (mean=29). Any score above 21 indicates fatigue.

### 4.3.2 Setup

The study was held at the homes of each participant. To ensure there were no issues with detecting eye blinks, the participants were asked to test their eye blinks prior to the study. Based on their detected eye blink ratio, the eye blink detection threshold was adjusted for each participant.

To assess subjective well-being, fatigue levels, and the degree of human-plant synchronicity, I employed the following assessment tests, respectively:

- Positive Affect Negative Affect Schedule (PANAS)
- Fatigue Assessment Scale (FAS)
- the Inclusion of Other in the Self (IOS) scale

The participants took these assessment tests before and after the study to analyse weekly changes. They also recorded their PANAS and IOS scores during the study to track daily changes.

PANAS is one of the dominant assessment methods used to measure mood or emotion. It evaluates subjective well-being using twenty items comprised of positive (e.g. excited) and negative (e.g. distressed) affect in 5-point Likert Scale. It is designed to accommodate measuring affect changes in a specific time period (e.g. day, week, or year). To gauge each participant's chronic fatigue levels, I used FAS since it offered simple yet effective means to measure chronic fatigue. It is comprised of ten items, five questions related to physical fatigue and the rest to mental fatigue. Each item is rated based on the 5-point Likert Scale. For assessing the degree of human-plant synchronisation, I used IOS which utilises a pictorial measure of closeness based on the degree of overlaps of two circles [43].

### 4.3.3 Procedure

During the study, the participants were asked to conduct the following tasks each day.

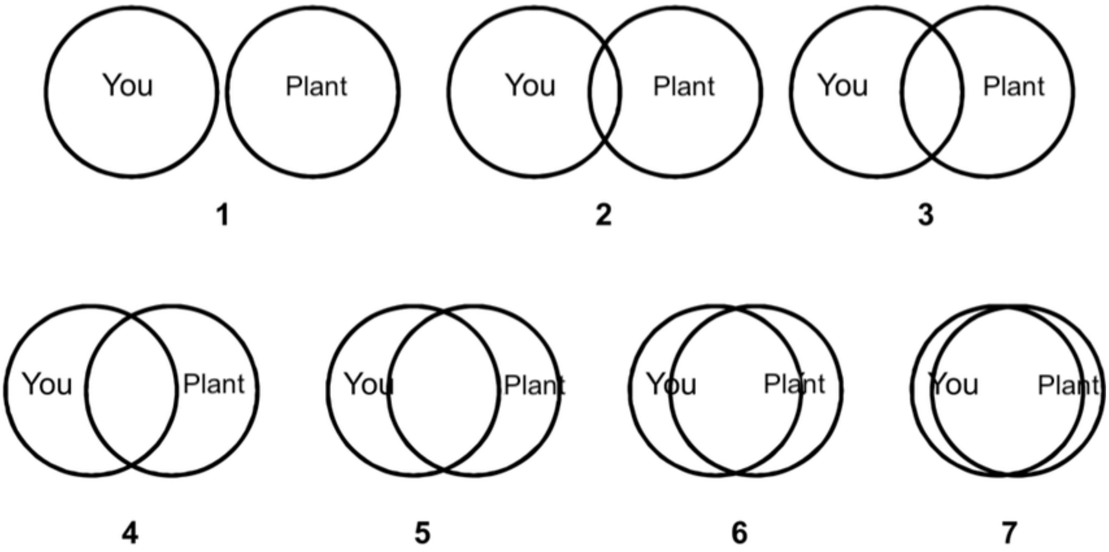

Figure 4.6 The Inclusion of Other in the Self(IOS) Scale used in the study

- Record eye blinks using the web application
- During the recording, conduct a Psychomotor Vigilance Task (PVT)
- At the end of the day, reflect on own fatigue level of the day
- Take the plant photo with the LEDs turned on
- Answer PANAS and IOS for the day

They were free to set the time for recordings but asked to remain consistent in the recording amount and time period. Three minute PVT was used as a ground-truth data for evaluating the correlation between the eye blink frequency and the reaction time. To support self-reflection, the participants were invited to use the colour of the grow LED as a guide for gauging their fatigue levels.

At the end of the study, the participants were provided with a set of graphs that visualised the changes in their eye blink frequency (as a proxy for fatigue levels), subjective well-being, and human-plant synchronicity (IOS) with plant photos they have taken over the period. They were then asked to review and reflect on their subjective well-being over the past week. After the reflection, they completed the post-study survey. Lastly, the participants were invited to answer anonymous user feedback to further inquire about their experience with the prototype.

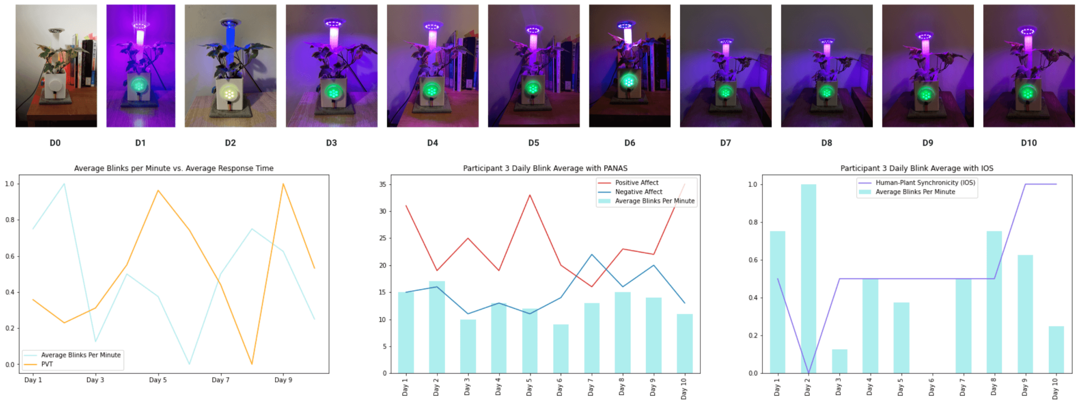

Figure 4.7 An example of the data provided to the study participants for the post-study reflection task

## Chapter 5

# Discussion and Future Work

Given how much of our world is still surrounded by uncertainty and in desperate need of better coping mechanism, the value of reflection cannot be exaggerated. Our obsessions with productivity and efficiency can make us feel we are always against time. But with reflection, we can better equip ourselves to weave through the complexity of everyday life and find clarity. Based on this belief, I proposed a bio-digital hybrid interaction system that utilises plant growth as a way to gauge and monitor human fatigue levels. The interaction system linked human physiological responses (eye blinks) with plant health, creating a sense of synchronicity between human well-being and that of plants. The study result showed that the devised human-plant interaction system contributed to an enhanced sense of synchronicity between humans and plants. In particular, we have seen a promising result on the impact of human-plant synchronisation on subjective well-being; the more people felt a connection to plants, the less their experienced negative affect.

However, further studies are required to observe the effect of having the prototype in a longer time frame as the user experience is expected to change as plants grow. The goal of achieving a symbiotic relationship between human and plant well-being is still far ahead.

# 5.1. Limitations

## 5.1.1 Assessing the Long-term Impact

There are some challenges that need to be addressed. In terms of the long-term impact of human-plant synchronisation, further study with a longer time frame is necessary to fully assess the effectiveness of the prototype. We will need to take account of the changes in habits and physiology (both humans and plants) among other seasonal variables. For example, while the study participants did not need to water their plants during the study, the situation will not be the same in summer when most plants need to be watered daily.

## 5.1.2 Representing Human Fatigue Levels

Overall, the study participants felt their fatigue levels were relatively well represented. However, as mentioned in chapter 4, the discrepancy in their daily subjective fatigue levels and the represented plant health caused some confusion. As there is a delay in visual feedback, such discrepancy cannot be avoided. Because the average eye blink frequency determines the colour of the grow LED, if users only record their eye blink data early in the day or a small fraction of the day, the collected data will not accurately represent their fatigue levels. Nevertheless, relying solely on eye blink detection puts a limitation on representing fatigue levels. To best represent users' fatigue levels, we need a system to collect both subjective and objective fatigue levels.

In addition, we need to consider other forms of fatigue assessment. While the browser-based application offered an unobtrusive solution to fatigue assessment, the use of web camera intervened with the other user activities. For instance, since the eye blink detection software collected eye blink data from a web camera, it inevitably limited the recording opportunity to while participants were at their desks. Also, using a web camera for fatigue assessment blocked video calls to be made; therefore, the software had to be shut off during video calls. Since video calls have become the new norm in the COVID-19 era, the software's inability to record eye blinks during video calls could undermine the overall user experience and expand the gap in subjective and objective fatigue levels.

Furthermore, we need to accommodate gender and individual differences in eye blink frequency. According to the study results, women tended to blink more frequently; the female mean minute eye blink rate was 15.95 as opposed to 9.2 for males. Also, since subjective fatigue is not universal, the same amount of eye blink frequency among different people may not necessarily mean they experience fatigue more or less the same. Therefore, rather than setting a unified eye blink frequency threshold upon determining fatigue, we should devise a flexible algorithm that can learn and adapt to individual differences.

### 5.1.3 Representing Plant Health

Due to the slow and subtle growth of plants, the plants' actual physiological data was not adopted for the study. Instead, light intensity, temperature, and humidity data were used as proxies for plant health. While accurately representing plant health was not a criterion for achieving a sense of human-plant synchronicity within the study time frame, a discrepancy in actual plant health and the proxy may emerge in the long-run which will undoubtedly affect the degree of human-plant synchronicity.

Also, visualising plant health in three colours does not fully represent the subtle and gradual nature of plants. While the colour coding system offered a simple and intuitive understanding of plant health each day, it did not communicate gradual changes. In response to the post-study reflection, one of the study participants pointed out that it was difficult to observe changes in the plant even with the photos. As much as it is challenging to visualise plants' organic changes in a human-understandable manner, it appears to be an indispensable element to build trust in the represented plant health.

## 5.2. Contributions

This research delved into approaches that best utilise slow interaction for the purpose of improving well-being, visualised the connection between human fatigue levels and plant health, evaluated the effectiveness of such visualisation method, and gain insights on the factors that further advance human-plant synchronisation for enhancing well-being. Lastly, this thesis contributed to the body of knowledge on human-plant interaction by introducing how human biosignals can be incorporated into the interaction. It will fill an existing gap in this area, and open doors for further research into the field.

In summary, here are the main contributions of this thesis:

- Designed a novel means to connect human biosignals with plant health as well as its visualisation method.
- Presented an in-the-wild evaluation study of a human-plant interaction system, which is still lacking in the majority of human-plant interaction research.
- Provided an evidence on how human-plant synchronisation can help diminish negative affect.
- Offered an alternative to experience human-plant interaction by posing plants as a medium to induce reflective experience.

## 5.3. Future Work

Future work will be built based on the contributions mentioned above. There are possible directions I can take moving ahead. First, since the reflective property of slow interaction can not only provide us with an opportunity to reflect on ourselves but also relationships with others, it would be interesting to evaluate how the prototype will be in use as a medium to remotely monitor fatigue levels of others. Such a scenario can even help people cooperate to maintain healthy mental states as well as recover from stress and anxiety better. The application scenario of this bio-digital hybrid interaction system can further extend beyond fatigue level monitoring and attend to both physical and psychological well-being. For example, personal data related to sleep performance or fitness data can be synced to plant health for better self-management. With human-plant synchronisation, we can cultivate our minds while cultivating nature.

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# Appendices

## A. Source Code

All source code for the eye blink detection application is uploaded to my GitHub account [1].

## B. Data Provided Prior to the Post-Study Survey

The 10-day overview data were provided to the study participants at the end of the study to facilitate the reflection on the past ten days.

## C. Surveys

In addition to the questions regarding weekly positive and negative affect and chronic fatigue levels, the additional questions were asked to evaluate the impact of the devised prototype.

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[1] https://github.com/michiminstar

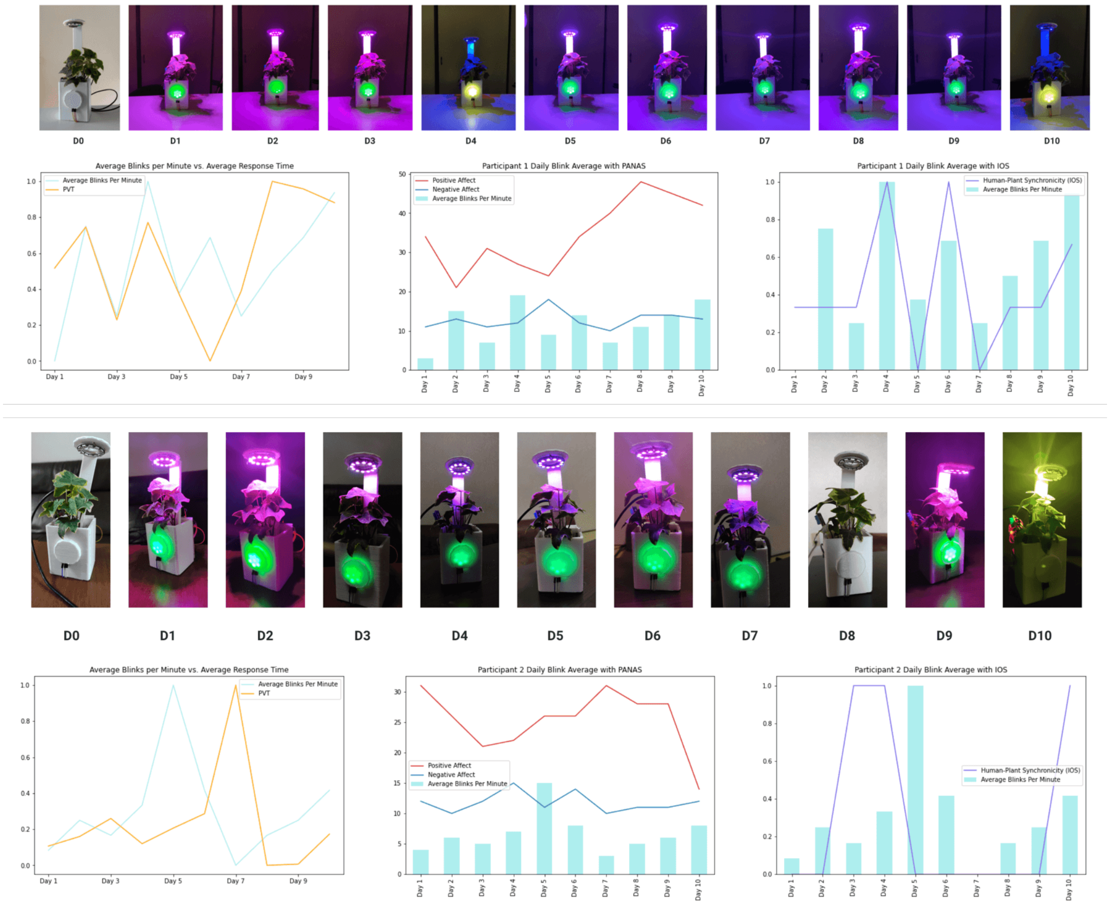


Figure B.1 The overview of the 10-day data used for self-reflection (participant 1 & 2)

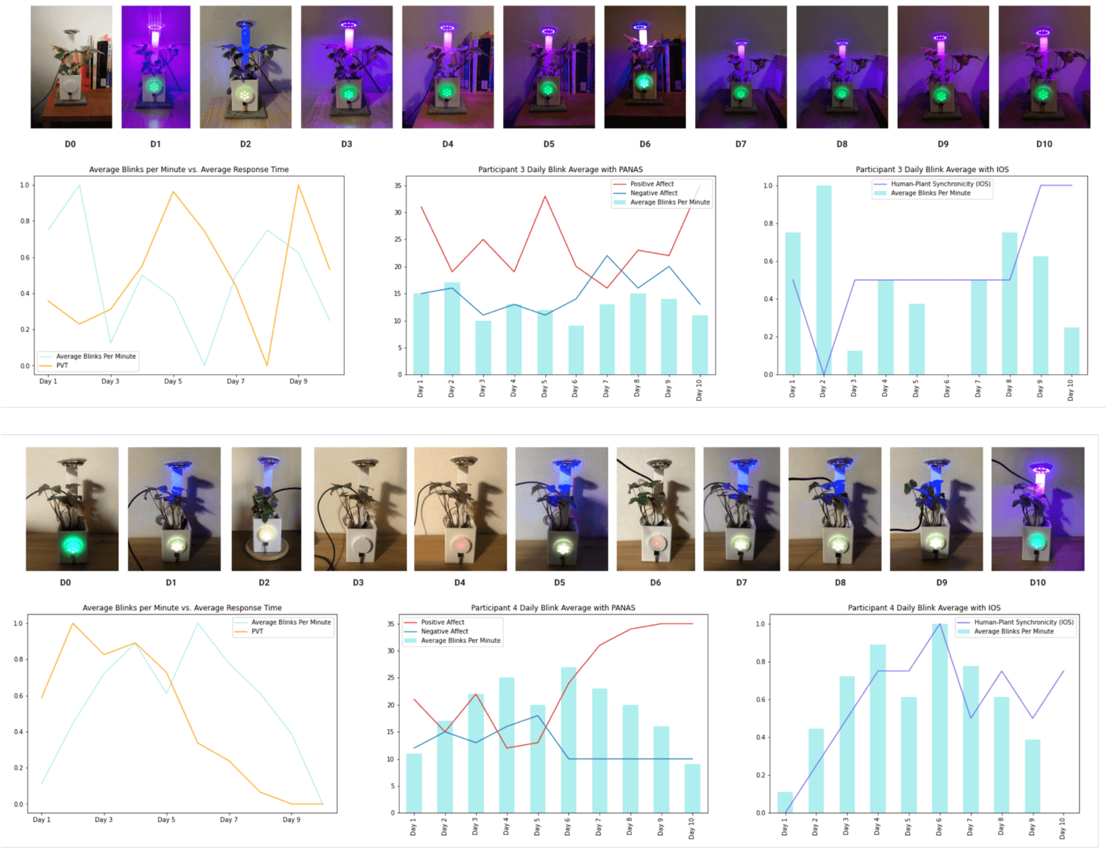
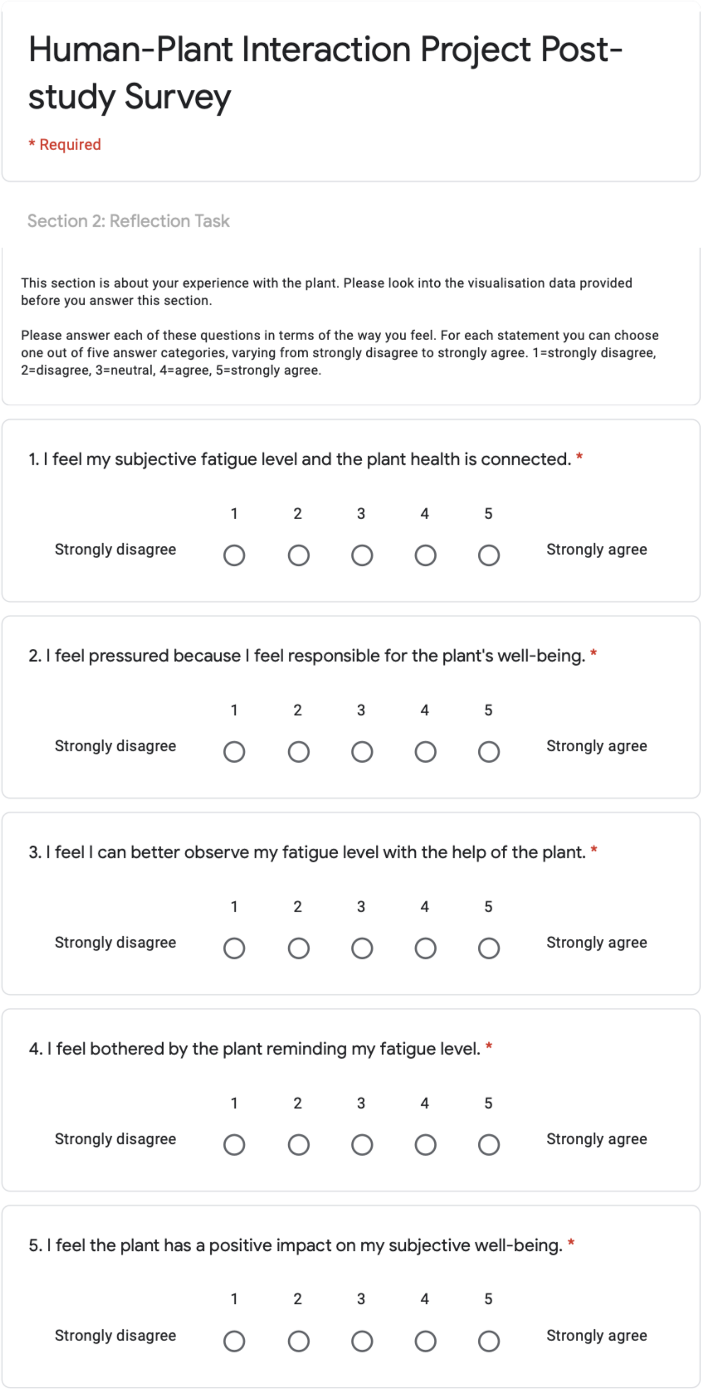


Figure B.2 The overview of the 10-day data used for self-reflection (participant 3 & 4)



# Human-Plant Interaction Project Post-study Survey

* Required

Section 2: Reflection Task

This section is about your experience with the plant. Please look into the visualisation data provided before you answer this section.

Please answer each of these questions in terms of the way you feel. For each statement you can choose one out of five answer categories, varying from strongly disagree to strongly agree. 1=strongly disagree, 2=disagree, 3=neutral, 4=agree, 5=strongly agree.

1. I feel my subjective fatigue level and the plant health is connected. *

| | 1 | 2 | 3 | 4 | 5 | |
|---|---|---|---|---|---|---|
| Strongly disagree | ○ | ○ | ○ | ○ | ○ | Strongly agree |

2. I feel pressured because I feel responsible for the plant's well-being. *

| | 1 | 2 | 3 | 4 | 5 | |
|---|---|---|---|---|---|---|
| Strongly disagree | ○ | ○ | ○ | ○ | ○ | Strongly agree |

3. I feel I can better observe my fatigue level with the help of the plant. *

| | 1 | 2 | 3 | 4 | 5 | |
|---|---|---|---|---|---|---|
| Strongly disagree | ○ | ○ | ○ | ○ | ○ | Strongly agree |

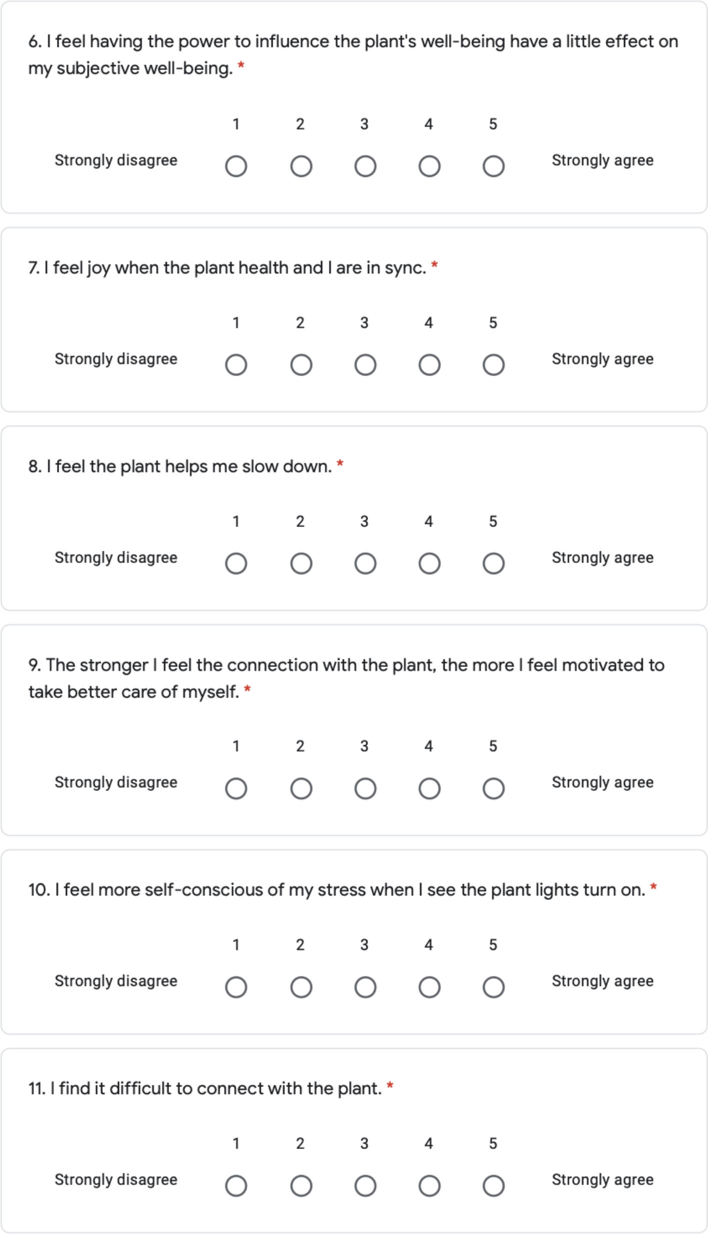
4. I feel bothered by the plant reminding my fatigue level. *

| | 1 | 2 | 3 | 4 | 5 | |
|---|---|---|---|---|---|---|
| Strongly disagree | ○ | ○ | ○ | ○ | ○ | Strongly agree |

5. I feel the plant has a positive impact on my subjective well-being. *

| | 1 | 2 | 3 | 4 | 5 | |
|---|---|---|---|---|---|---|
| Strongly disagree | ○ | ○ | ○ | ○ | ○ | Strongly agree |

Figure C.1 Reflection questions in the post-study survey 1 of 3



6. I feel having the power to influence the plant's well-being have a little effect on my subjective well-being. *

| | 1 | 2 | 3 | 4 | 5 | |
|---|---|---|---|---|---|---|
| Strongly disagree | ○ | ○ | ○ | ○ | ○ | Strongly agree |

7. I feel joy when the plant health and I are in sync. *

| | 1 | 2 | 3 | 4 | 5 | |
|---|---|---|---|---|---|---|
| Strongly disagree | ○ | ○ | ○ | ○ | ○ | Strongly agree |

8. I feel the plant helps me slow down. *

| | 1 | 2 | 3 | 4 | 5 | |
|---|---|---|---|---|---|---|
| Strongly disagree | ○ | ○ | ○ | ○ | ○ | Strongly agree |

9. The stronger I feel the connection with the plant, the more I feel motivated to take better care of myself. *

| | 1 | 2 | 3 | 4 | 5 | |
|---|---|---|---|---|---|---|
| Strongly disagree | ○ | ○ | ○ | ○ | ○ | Strongly agree |

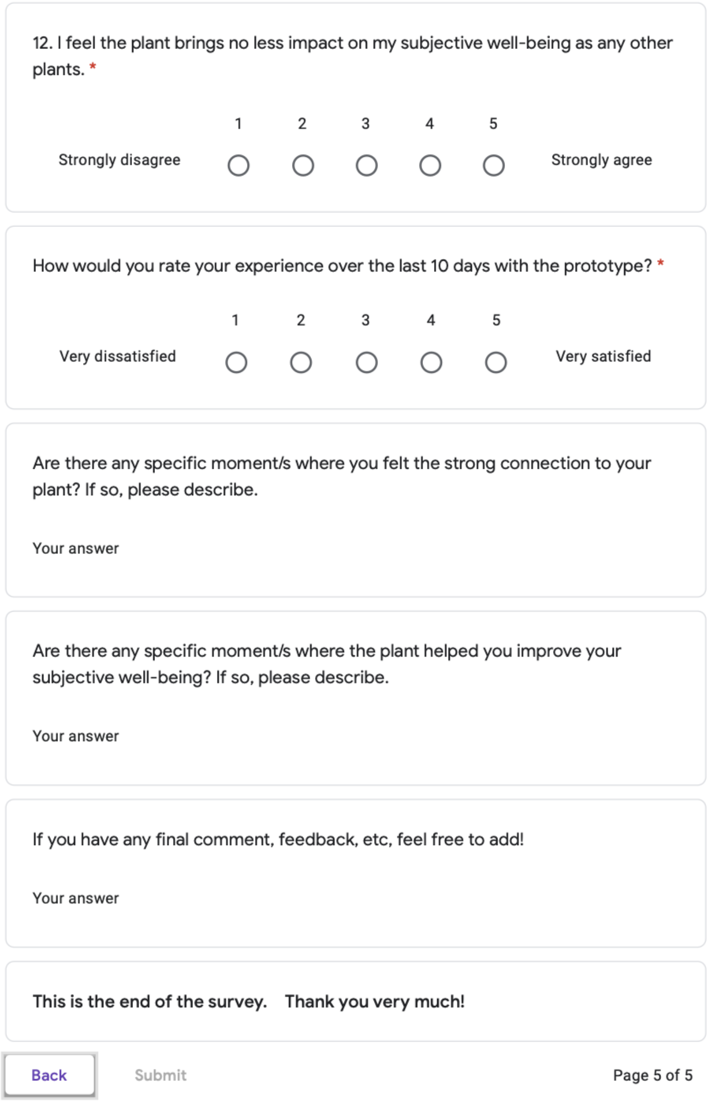
10. I feel more self-conscious of my stress when I see the plant lights turn on. *

| | 1 | 2 | 3 | 4 | 5 | |
|---|---|---|---|---|---|---|
| Strongly disagree | ○ | ○ | ○ | ○ | ○ | Strongly agree |

11. I find it difficult to connect with the plant. *

| | 1 | 2 | 3 | 4 | 5 | |
|---|---|---|---|---|---|---|
| Strongly disagree | ○ | ○ | ○ | ○ | ○ | Strongly agree |

Figure C.2 Reflection questions in the post-study survey 2 of 3



12. I feel the plant brings no less impact on my subjective well-being as any other plants. *

| | | | | | | |
|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | |
| Strongly disagree | ○ | ○ | ○ | ○ | ○ | Strongly agree |

How would you rate your experience over the last 10 days with the prototype? *

| | | | | | | |
|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | |
| Very dissatisfied | ○ | ○ | ○ | ○ | ○ | Very satisfied |

Are there any specific moment/s where you felt the strong connection to your plant? If so, please describe.

Your answer

Are there any specific moment/s where the plant helped you improve your subjective well-being? If so, please describe.

Your answer

If you have any final comment, feedback, etc, feel free to add!

Your answer

This is the end of the survey. Thank you very much!

Figure C.3 Reflection questions in the post-study survey 3 of 3