Cyano-chromic Interface: Aligning Human-Microbe Temporalities Towards Noticing and Attending to Living Artefacts

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ABSTRACT

Microbes offer designers opportunities to endow artefacts with environmental sensing and adapting abilities, and unique expressions. However, microbe-embedded artefacts present a challenge of temporal dissonance, reflected by a "time lag" typically experienced by humans in noticing the gradual and minute shifts in microbial metabolism. This could compromise fluency of interactions and may hinder timely noticing and attending to microbes in living artefacts. In addressing this challenge, we introduce *Cyano-chromic Interface*, in which photosynthetic activity of cyanobacteria (*Synechocystis* sp. PCC6803) is timely surfaced by an electrochromic (EC) material through its monochromatic display. Grounded through interface performance characterization and design primitives, we developed application concepts through which we instantiate how the interface can be tuned for diverse functional and experiential outcomes in living artefacts. We further discuss the potential of aligning human-microbe temporalities for enriched interactions and reciprocal relationships with microbes, and beyond.

CCS CONCEPTS

• **Human-centered computing → Systems and tools for interaction design**.

KEYWORDS

Biological-HCI, microorganisms, surfacing livingness, temporality, living media interfaces, microbial displays, cyanobacteria, human-microbe interactions

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1 INTRODUCTION

Distinct biological affordances of microbes offer unique functional advantages in biodesign, such as sensing and displaying, purifying, and energy-generating capabilities. As such, they have been the subject for much discourse in HCI [48], in the design of novel living media interfaces [71] [5] [28], sensing devices (e.g., [67][81]), ambient displays (e.g., [14][31]), public art installations (e.g., [58][2][32]), and games (e.g., [51][56][76]).

As one of the most abundant and diverse life forms on earth [62], microbes play an intrinsic role in almost every natural cycle, supporting the existence of all higher trophic lifeforms, and the health of the global climate [10]. Also for us humans – one of the many co-habitants existing on the planet – our microbial "companion species" [34][33][35] have also been, and will continue to, profoundly shape the ways in which we live and experience the world.

1.1 Temporal Dissonance and Alignment with Microbes

As we recognize the value of microbes in inspiring the design of novel interactive systems, "bringing their livingness to our senses" ([42], p.45) is important. However, there may be challenges involved with the *surfacing* [49] process, due to technical constraints, of microscopic size and the apparent slowness in response to stimuli. In this paper, we tap into one such challenge, namely "temporal dissonance", that exists between humans and microorganisms, as one of the initial hurdles that designers need to overcome.

Multiple biochemical reactions take place in a living organism as part of their metabolism. These processes can assume multiple aesthetic expressions in living artefacts over time, in the form of changes in colour and pattern, etc. (i.e., *living aesthetics* [42]).

However, as such changes are often minute, we may struggle to adequately perceive them with sufficient sensitivity. To further illustrate our point, we analyse the phenomenon of oxygenic photosynthesis - a ubiquitous process in plants and a group of microbes including cyanobacterial species (e.g., *Synechocystis* sp. PCC 6803 [41]) - which has been crucial for Earth's transition to the present oxygen-rich atmosphere [6]. Unaided human perception of accumulating chlorophyll - a green-coloured indicator of cyanobacteria growth rate – is difficult (if not impossible) to achieve in real time, due to the granularity of the biochemical processes involved. Hence, if there is a persistent disruption in the organisms' metabolism, which would potentially affect its photosynthetic activity - humans would only notice this a couple of days later, when the colour turns pale, which might be too late to effectively act upon. We call this a *temporal dissonance*; a type of mis-alignment of temporalities between microbial metabolism and human senses.

Moving forward, we argue that such type of temporal dissonance would hinder humans from timely noticing of microbes, which may pose challenges to *fluency of interactions* [65][36][66] with living artefacts and potential barriers towards attending to their vitality. Focusing on the aforementioned cyanobacterial species, we therefore investigate the possible scientific and designerly ways of aligning temporalities between humans and microbes, bringing imperceptible changes in microbial metabolisms more noticeable to humans. To achieve this, we propose a multifaceted approach, starting with immersing ourselves into the life of microbes to initiate the identification of 1) the challenge of temporal dissonance, 2) a surface-able metabolic activity of the microorganism, 3) an appropriate complementary media that would facilitate in addressing such challenge. Following this, we designed and characterised an interface through which the complementary media is synergized with the microorganism to achieve a temporally-aligning interface, which was subsequently imagined and situated in everyday living artefacts.

1.2 Contributions of the Paper

This paper introduces a novel microbial interface that aligns temporalities of humans and cyanobacteria - which we call the *Cyanochromic Interface*. It consists of cyanobacteria and an electrochromic (EC) material - an electricity-driven and monochromatic display that manifests the gradual and minute shifts during cyanobacterial photosynthesis, at a more perceivable rate and magnitude. By presenting design primitives of the interface, grounded through scientific characterisation, we offer designers starting points for living artefacts that can be situated in diverse use contexts through configurations of their components. We discuss how the interface can be tuned for diverse functional and experiential outcomes in living artefacts. Through the generated application concepts we demonstrate the potentials of the interface towards fostering reciprocal human-microbe relations in everyday scenarios.

2 RELATED WORKS

2.1 Designing Microbial Interfaces

Biological-HCI (also known as "bio-HCI") [79] is an emerging community within HCI that recognizes the distinct possibilities afforded through the integration of biological materials (e.g., plants, fungi, bacteria) and processes, and explores design possibilities that may open up. A body of research in bio-HCI has emerged, examining the roles microorganisms could play in our everyday lives. These include design frameworks, such as *Living Media Interfaces (LMI)* [71] and *Living Bits* [79], and design taxonomies [98] that characterises the computational relationship between microbes and the digital worlds. These corpus of works in HCI include the exploration of microbe-driven applications, including novel interfaces (see, for an extensive overview, [49]), sensing devices (e.g., [67][81]), ambient displays (e.g., [14][31]), public art installations (e.g., [58][2][32]), and games (e.g., [51][56][76]).

In introducing *living artefacts* [42] – artefacts in which the livingness of the organism extends to the "use-time" of the artefact – [42] called for an alternative biodesign approach that foregrounds livingness as a biological, experiential, and ecological phenomenon, which could lead to a more sustainable relationship between humans and living organisms. One of the strategies proposed by the authors has been to frame the process around *living aesthetics*. Described as the way humans experience the type, degree, and duration of change in a living artefact over time (e.g. immediate or gradual changes in colour, form, or function), living aesthetics is positioned as a desirable design element that may evoke meanings, associations, and emotions, but could also be crafted for indicating the organism's struggle or wellbeing, and eliciting unique care actions in the long run, i.e., facilitating the *mutualistic care* [42] between humans and the living organism. HCI researchers showed practical explorations of tuning and characterising living aesthetics in *Living Colour Interfaces* [28] and *Living Light Interfaces* [5]. We aim to extend these growing conversations in biological-HCI, by reporting on our investigations on cyanobacteria (*Synechocystis* sp. PCC6803).

2.2 Cyanobacteria as a Design Medium

Cyanobacteria, also known as "blue-green algae", are one of the oldest life forms on earth, with fossil records dating back to 3.2 billion years ago [85]. This group of microorganisms can be present in a vast variety of habitats, from aquatic to terrestrial, including hypersaline, deserts, polar and hot springs [88]. Their capability to perform oxygenic photosynthesis and synthesise organic compounds distinguishes cyanobacteria from other bacteria. As photosynthesizing organisms, cyanobacteria can metabolise with only light, water, carbon dioxide, and other inorganic substances. In order to survive, they constantly absorb sunlight and carbon dioxide while releasing oxygen to the atmosphere, a process called carbon fixation, which is a major component of the global carbon cycle [9]. During exposure to light, green biomass accumulates over time (within a time span of days and weeks), converting the total amount of light absorbed into its living colour. In this process they also generate a small amount of electricity [69][68][95], the design and scaling up potential of which has been explored by [84].

Photosynthetic microbes have been integrated in several recent designs (figure 1) that function as part of energy converter [24], interactive air purifying playground [23], air purifying garment [1], outdoor water-detoxing tiles [29], light-responsive image display [27], and electricity producing wallpaper [84]. However, their

Figure 1: Living artefacts integrating photosynthetic microbes. A. *Living Things* ©Ethan Frier and Jacob Douenias; B. *AirBubble* ©Maja Wirkus for ecologicStudio; C. *Biogarmentry* ©Roya Aghighi; D. *Indus* by Indus by Dr. Shneel Bhayana, Dr. Brenda Parker and Prof. Marcos Cruz, Bio-Integrated Design Lab, UCL. Photo ©Andy Stagg E. *Algae-graph* ©Lia Giraud; F. *Algae Printing* ©Marin Sawa in collaboration with Imperial College London (Peter Nixon and Klaus Hellgard), the printed artifact for electricity generation in collaboration with Andrea Fantuzzi.

potential as an interactive living media for HCI hasn't been explored to date. Following an existing technical framework [84], we focus on cyanobacterium *Synechocystis* sp. PCC6803 as a relatively simple photosynthetic microbe and a model organism in science, as a starting point for our research. Inspired by the notion of *living aesthetics*, we first turn our attention to the peculiar ways cyanobacteria change and evolve over time; its temporality.

2.3 Temporality of Microbes in HCI

An historically extensive corpus of research on temporality in HCI has been driven by the idea of improving computer system response times (e.g., reducing input-output latency) under the premise of enhanced machine efficiency and use productivity [17]. Contrastingly, other scholars have explored divergence of temporalities[20, 30, 38, 51, 63, 73, 78], such as the concept of "slow technology"[30], which re-positions technologies as a tool and a medium towards fostering slow interactions in our everyday lives. By doing so, they argue, slowness would invite opportunities for reflection, solitude, mental rest, and contemplation (e.g., [13][59][73][75][74]). In addition, in design literature, one thread of discussion concerns the notion of *Temporal Design* [82] acknowledges the multiple dimensions and narratives around time, towards their implementations beyond the aforementioned ends.

Scholars exploring living organisms as an interactive "biocomputational material" [80][71] have proposed possible contrasting ways in which the non-human temporalities of microbial species could be remedied through design. On one hand, some have framed microbes' slowness as a design opportunity (e.g., [55][54][78]), a tool for human conditioning (e.g., patience [7]), and as a productive design element that could be integrated towards enhancing user experiences (e.g., [51][50][7]). On the other hand, some have framed the slowness of biological response and the resulting temporal misalignment between humans and microbes as a challenge for interaction design. They see it as a negative feature that may compromise the fluency of interaction and associated user experiences (e.g., [47][56][2][76] [32]), whilst exploring hardware and software solutions that could enhance or augment the organism's response to stimuli (e.g., [25]).

We recognize the unique temporal expressions of cyanobacteria, i.e., its living aesthetics, and how this could be unlocked as a design potential in living artefacts (as explored by other biodesigners discussed in the previous section). However, whilst we acknowledge that utilising slowness and temporal dissonance in their natural form can offer alternative experiential opportunities for the prospective users of living artefacts, doing so may not necessarily prove beneficial for microbes' survivability.

Approaches to tackle temporal dissonance in Bio-HCI. Researchers explored theoretical frameworks and approaches to temporality that are also beneficial for living organisms, either by *translating microbiological phenomena* [49] or environmental data, to more human-comprehensive forms [11][89][91][8]. In Tardigotchi [22], a water bear's temporality is revealed to humans in real-time through a displayed digital microbial avatar that communicates whether the real water bear is hungry or satisfied. Text messages remind the user to feed the microbes on time. Similarly,

Nukabot [12] is an artefact that communicates the needs of food-fermenting bacteria, through the use of a vocal user interface and cultural symbols, that are both designed to emotionally appeal to the human users. By doing so, the users are encouraged to regularly stir the fermenting bran as a way to deliver regular care to the microbes in order for the microbes to continue produce food for humans (i.e., mutualistic care). These two designs both facilitate temporal alignment towards care, through timely reminders that would maintain their respective microbial vitality. Other scholars exploring temporal alignment include Armstrong[3], whose work *Active Living Infrastructure: Controlled Environment (ALICE)* [3] proposes a platform with which humans can engage in real-time conversations that are sensitive to fluctuations of microbial physiology. Delivered through the use of electrical signal sensing, digital simulation with artistic representation ([3], p.11-12), the artefact calls for a more sensitive approach towards the seemingly invisible and slow microbial worlds.

In this paper, we have extended these existing HCI explorations by designing a *Cyano-chromic Interface*, to address the temporal dissonance between humans and cyanobacteria. Similar to *ALICE*, we aim to translate fluctuations in microbial metabolism (electrical signal of cyanobacteria) to be perceived by humans, with enhanced sensitivity. In our case, however, the means with which the translation is displayed are not digitally simulated. But rather, they are manifested through its materiality, specifically with electrochromic visualisation involving colour change, an alternative avenue for interpretation. Furthermore, the primitivity of the interface is given prominence, as building blocks that are open for customised artefact construction whilst yet to be highly configured.

The *Cyano-chromic Interface*, with its sensitive, chromatic, and customisable features, would naturally require multi-phase development, consisting of scientific grounding and design instantiations. In the following section, we outline these phases in further detail.

3 CYANO-CHROMIC INTERFACE

3.1 Methodology

Our research, informed by material-driven design [43], combines different design, science and engineering techniques to help zoom in and out the microorganism - cyanobacteria - for its thorough understanding and to explore the relationships between the various material components of the interface. We started with a sensitising study by the first author, during which the author lived with cyanobacteria for three months. This part concludes with the insight of the design challenge of temporal dissonance and a technical inquiry to identify a potential complementary media that can be utilised to timely surface cyanobacterial metabolism, and thus address the challenge. Second, an interface was designed by coupling the chosen media with cyanobacteria. Then we conducted controlled lab experiments to characterise and validate the working principle of our interface, which provided the foundation for the next step of generating design primitives. And finally, the primitives were utilised subsequently in generating and illustrating the application concepts.

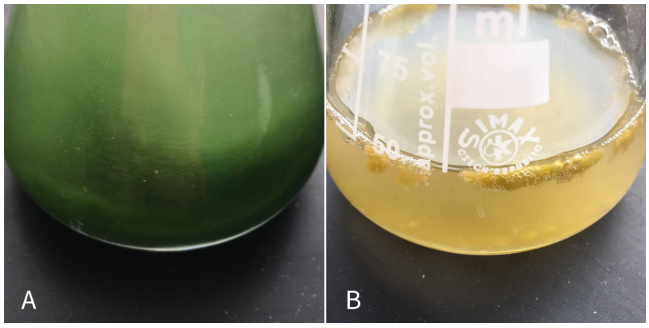

Figure 2: Cyanobacteria cultures at different conditions A) a healthy culture with a dark green hue B) a culture that has been damaged by direct sunlight characterised by its yellow-brown appearance

3.2 Sensitising with Cyanobacteria

To become immersed with cyanobacterial life, as a way to familiarise with their temporality, the first author lived with the cyanobacterium *Spirulina* platensis (a commercially accessible strain and a substitute for *Synechocystis* sp. PCC6803) for three months in a (home) design studio.

The cyanobacterial culture and its nutrient solution were contained in a transparent glass bottle. During the author's daily encounters with cyanobacteria, the culture was divided into multiple glasses, and placed on a south-west facing window sill. Carefully formulated nutrients were added to placate the needs of the microbial companions at intervals which were deemed most suitable through observing culture density. Light qualities had a substantial impact on the health of the culture: if the culture was under constant and moderate light in the day, its colour would appear greener over *days*, until a dense, dark green colour over *weeks*; due to growth and reproduction of cells (figure 2, A). However, during the time of cohabitation, a few of the cultures were damaged, when they were exposed to direct sunlight for too long. The culture colour became yellow-brown in a few days (figure 2, B), which could not be revived. On reflection, these damages could have been avoided with a timely reminder that would signal the struggles of the microbes to the author, who would have taken appropriate care actions.

The sensitising experience thus helped us to identify our design challenge - a temporal dissonance between humans and cyanobacteria - demonstrated by the fact that the vitality of cyanobacterial cultures is usually noticed late. Furthermore, it inspired us to focus on photosynthesis as the metabolic activity that we aimed to surface. We envision that a complementary media, which could help the organism express its timely photosynthetic wellbeing, would help to address this temporal dissonance.

3.3 The Interface

This section presents the design and the making of a temporal-aligning interface, which we call Cyano-chormic Interface. We focused on light intensity as the influence factor for cyanobacteria photosynthetic health, which we aimed to timely surface.

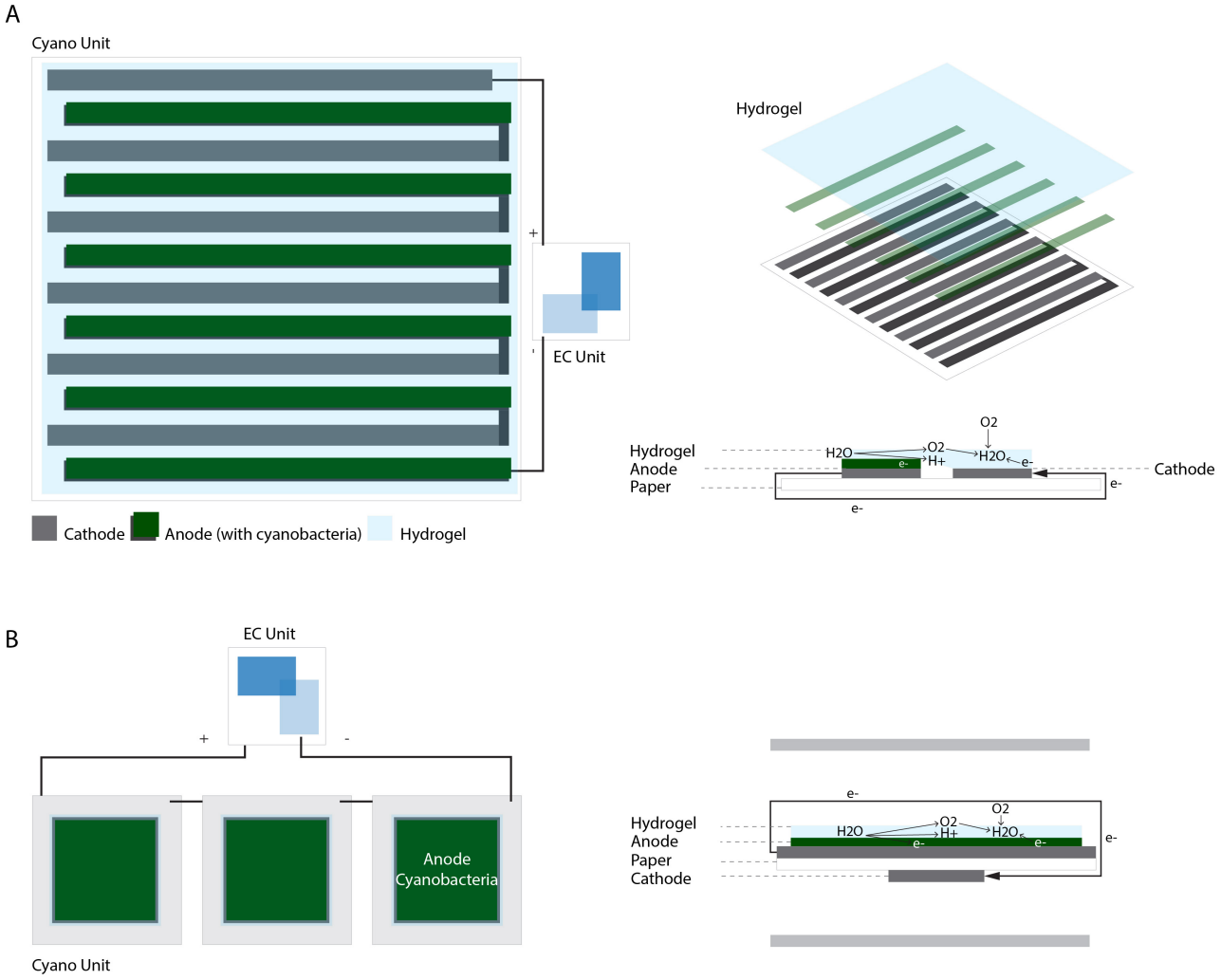

Figure 3: System architecture of the Cyano-chromic Interface, illustrating two possible configurations. A: Coplanar configuration enabling exposure of both electrodes in a single surface plane. B: Stacked configuration consisting of electrodes on layered surface planes.

This was enabled by using a complementary media - namely electrochromic material - with which the architecture of the system was designed, and its characterization was conducted, in the development of Cyano-chromic Interface.

3.3.1 Electrochromic Material As Complementary Media. We filtered through a few potential media (within the scope of smart materials and meta-materials) with the following criteria: (1) it directly receives input (such as oxygen, electrons, etc.) from cyanobacteria cells to function; (2) the output modality has similar sensorial qualities as living aesthetics of the organism (i.e. colour change); and (3) it can be adapted for integration in everyday artefacts. Based on these criteria, we ultimately focused on one media based on electrochromism, a phenomenon in which a material displays changes in colour or opacity in response to an electrical stimulus [15]. For this, we used an electrochromic material (EC) - PEDOT:PSS (poly(3,4-ethylenedioxythiophene) polystyrene sulfonate) [39], which can be integrated into a sheet material that can switch colour from light blue to dark blue upon electrical stimulation, received from cyanobacteria. Since the microbe can generate twice the amount of electricity under light conditions than in the dark [84], we harnessed such a difference in electrical current to trigger the EC displaying different shades of blue.

3.3.2 System Architecture. The interface is designed to allow the EC material to be stimulated by electrons generated during cyanobacterial photosynthesis, based on a technology called biophotovoltaics (BPV). Through assembly of BPV systems, electricity generated by

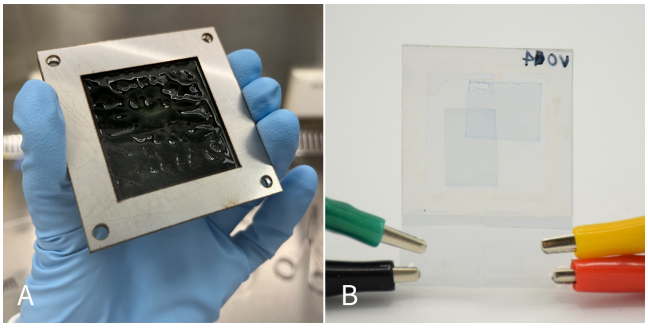

Figure 4: An assembled stacked cyano unit (A); An assembled EC unit (B)

the microbe can be utilised to power external devices. For the component that hosts cyanobacteria (i.e. cyano unit in figure 3), we tailored an existing technical framework of BPV construction [84]. The protocol suggests using an ink-jet (bio)printing method for fabricating the BPV system on a paper substrate. In this method, anode and cathode conductive inks are printed onto the paper, followed by the printing of the bio-ink containing cyanobacterial cells. Through electron transfer between anodes and cathodes, electrical current can be harvested in a closed circuit (figure 3). We adopted the protocol's paper-based design for constructing the cyano unit, due to its compact size and interaction potentials. Extending the approach of [84], we adopted a direct-ink-writing (bio)printing (an extrusion-based additive manufacturing method) [87] for fabrication of the cyano unit. To ensure brevity of this paper, we have moved further technical details and construction methods to Appendix.

The architecture (figure 3) of the Cyano-chromic Interface consists of four major components: 1) Cyano unit(s), where cyanobacteria are located, 2) EC unit(s), and 3) the paper substrate, 4) hydrogel sheets, which supplies nutrients and water to the microbe. The cyano units need to be exposed to light, under which their photosynthetic activity can generate electrical current supplying to the EC units in a closed circuit. Figure 3 includes an example primitive of the EC unit, consisting of two fields of pigment, one becoming dark blue upon electrical stimuli.

As in figure 3, the cyano unit can be configured in two ways: coplanar (figure 3, A) and stacked (figure 3, B). In a coplanar configuration, the anode and cathode materials are printed on one substrate, which makes the interface more compact, pliable, and allows for precise design and customization of electrodes. In a stacked configuration, in contrast, the anode and cathode components are vertically layered, which makes the interface easier to assemble, and thus are usually used for initial performance characterisation.

3.4 Characterization of the Interface

To validate our interface design, we undertook several characterization tests of the cyano unit, EC unit and the interface performance, which are outlined below.

3.4.1 Cyano Unit Characterisation. Characterisation of the cyano unit was based on the existing protocols presented by [68, 69, 84]. Potential output of the stacked cyano unit (figure 4, A) was measured by loading an external resistance (100 kOhm) over light and dark periods (1hour/1hour, illumination in the light period at 100 μmol $\cdot$ m^{-2} $\cdot$ s^{-1}). Figure 5 shows the responding potential output to light and dark situations in 2.5 cycles. The result suggested that the cyano units can periodically generate relatively higher electricity in the light, than in the dark conditions. No negative control (with only the culture medium) was performed because we reset the baseline current in every measurement by draining the stock current until stabilisation.

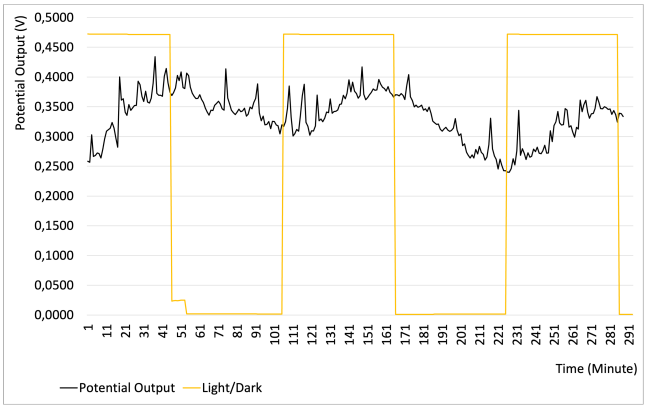

Figure 5: Voltage output to an external resistor (100k Ohm) over two and half light/dark cycles (1hour/1hour, illumination in the light period at 100 μmol $\cdot$ m^{-2} $\cdot$ s^{-1})

3.4.2 EC Unit Characterisation. This characterization involved testing the degree and duration of colour change of the EC unit based on different supply voltage and current. The colour change has two phases: charging and stabilising. In the charging phase, the EC material draws a peak current upon its connection to the power supply, and drops to a lower value within a few seconds to reach a stabilising phase. The current remains a low value afterwards. Each EC unit has its own internal resistance R(ec) that consumes a minimum amount of energy in the stabilised phase. The end state voltage on the EC can be summarised by the following equation:

$$U(end) = I(stable) \times R(ec) \quad (1)$$

The EC unit used in the test was composed of two visually overlapping rectangles on opposite electrodes (figure 4, B); when charged, the rectangle on the anode side becomes darker. A test was done to understand whether current supplied by cyano units gets transferred to the EC can stimulate observable colour change. To sustain low peak current which cyano units can potentially supply, a variable resistor was connected in series to the EC unit, and adjusted to ensure that the current supplied to the EC unit was between the ranges of 0-10 µA. The EC unit darkened its colour with a greater change at a higher peak current supply (figure 6). The colour change duration ranged between 9 to 13 minutes.

To conclude, the colour difference of an EC unit driven by the simulated cyano-unit currents was perceivable, which provided adequate technicality to our follow-up investigation on characterising the overall interface performance.

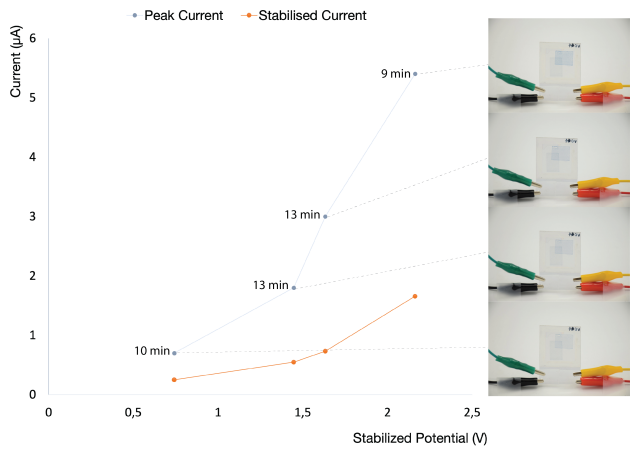

Figure 6: Understanding how peak current influences colour changing time and end state colouration

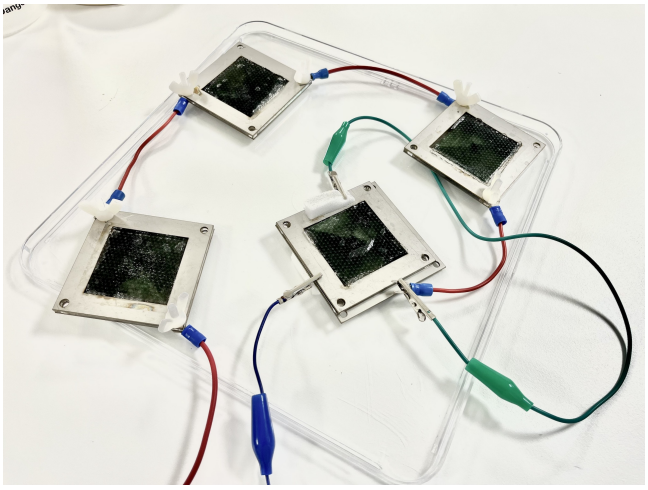

Figure 7: Four cyano units are connected in series

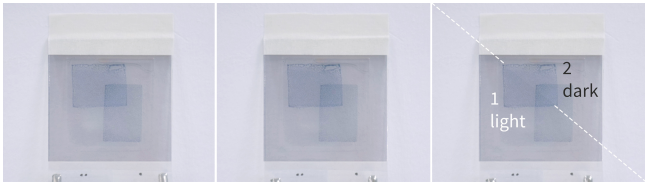

Figure 8: Response of the cyano-chromic interface to dark-light conditions. The top-left rectangle of the EC material changed colour from lighter to darker blue from dark (left) to light (middle) period. The colour comparison (right) of the EC material of the two states.

3.4.3 Cyano-chromic Interface Characterisation. Four cyano units were connected in series (figure 7) to an EC unit and placed in an incubator (with Relative Humidity of 98%) with mounted white LEDs. The cyano units were first kept under darkness for 1 hour

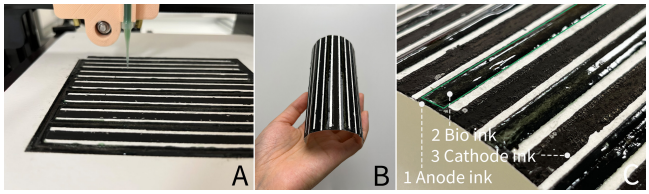

Figure 9: A fully printed coplanar cyano unit, on paper (B); Printing process (A); Close-up view (C): 1) anode ink 2) cyanobacteria in hydrogel 3) cathode ink

and then exposed to illumination of 100 μmol $\cdot$ m^{-2} $\cdot$ s^{-1} for 1 hour. Colour states of the EC unit were photographed before and after each period. At the end of the light period, the EC unit increased its colour intensity (figure 8).

The colour change from dark to light period was observed to be subtle (as shown by figure 8). However, we argue that by tuning the components in the system, one can potentially obtain a more prominent colour change, for instance, by increasing the number of cyano units [84], cell density [69], conductivity of electrode materials [84]. For instance, by increasing the number of cyano unit from 4 to 20, one can achieve 2 volts to power the EC unit under the light condition (as in our test), and 1 volt under the dark condition. According to figure 8, this would make the colour difference between light and dark periods more prominent.

3.5 Printability of the Cyano-chromic Interface

To further help the grounding of interface design, we continued to demonstrate the printability of cyano-unit in a coplanar configuration (figure 3, A). Anodic and cathodic conductive inks were printed onto a robust watercolour paper ($300g/m^2$) substrate, in a semi-staggered and semi-overlapping pattern (figure 9), to enable both polarities in a single surface plane. As a last step, the bio-ink was printed onto the anode area. This configuration offered high surface area for printing, whilst providing a flatter and thinner (and potentially more flexible) area for the interface to function, which inspired the generation of our design space.

4 DESIGN SPACE

In this section, we present a design space for the Cyano-chromic Interface, illustrating its potential to be integrated in everyday artefacts. Here, we explore the possible ways in which temporal alignment between the human and the microbe, aided by the interface and its associated designs, could help to address challenges that stem from temporal dissonance. We begin the chapter with some design primitives of the Cyano-chromic Interface to provide the general backdrop for interface variations and application concepts.

4.1 Design Primitives

We exemplify design primitives of the interface, including the cyano unit, the EC unit and interface configurations, which can be multiplied, combined and oriented for various functions and aesthetics.

4.1.1 Cyano unit. The cyano unit can be customised according to the desired pattern and printing method. The width of the electrodes should be within the approximate range of 1 to 6 mm, to allow for

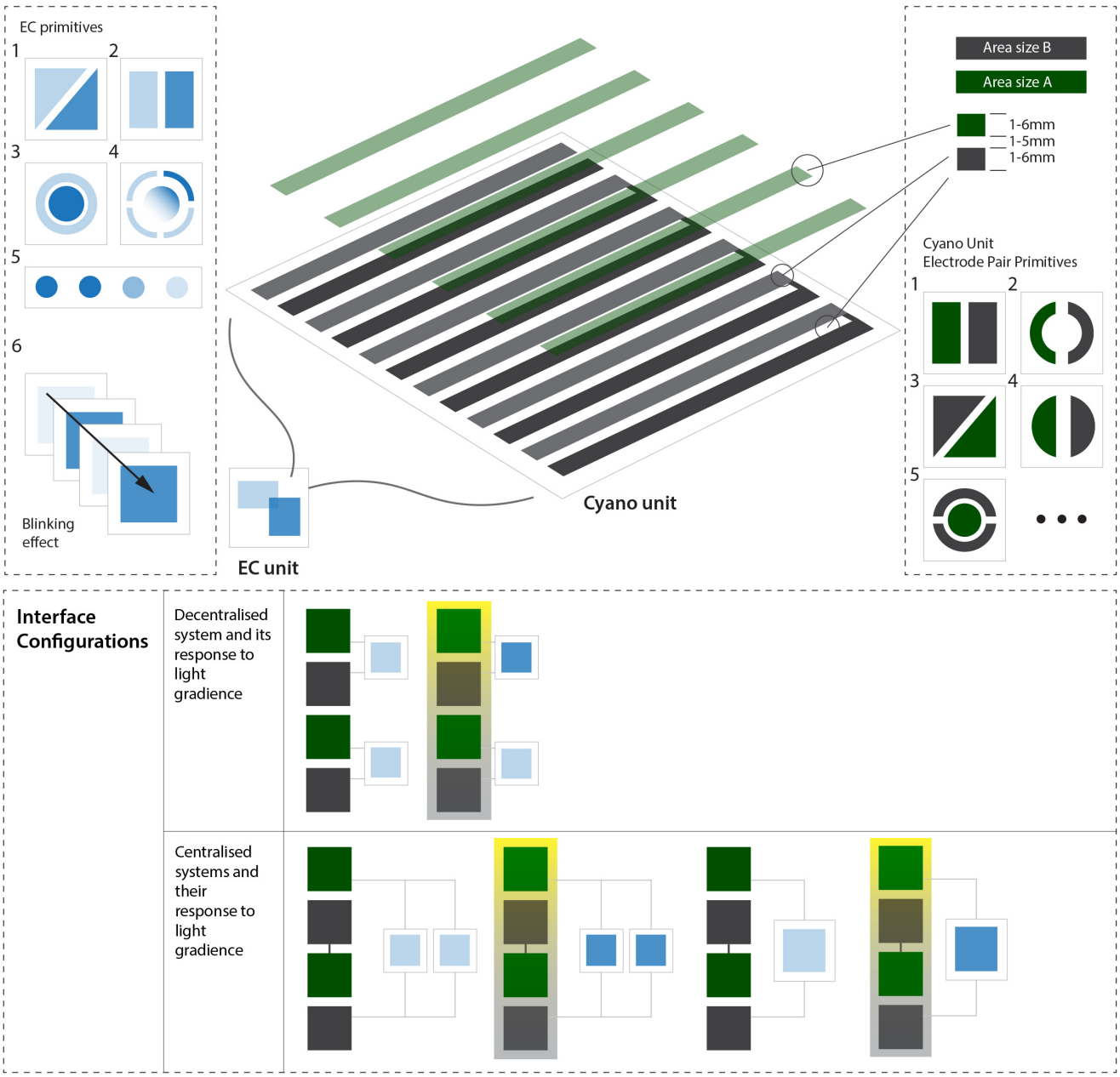

Figure 10: Design primitives of the interface: Variations of cyano units, EC units, and interface configurations

efficient proton exchange [64]. Area size ratio between the anode (green) and the cathode (black) should be roughly 1:1. We provide some examples of anode-cathode shape pairs (no.1 - 5 in figure 10).

4.1.2 EC unit . The EC unit can be varied in qualities of colour change, including intensity, gradient, and speed [39]. We provide five examples of EC shapes, for various visual effects (figure 10 top left, numbers 1 to 6). For example, the 5th shape (in figure 10) shows a "levelling up" effect; with current supplied, circles can change to dark blue in sequence. Through the use of capacitors that would store the electricity generated by the cyano unit [84], one can supply periodic bursts of energy to the EC, achieving a blinking effect (figure 10, no.6).

4.1.3 Interface Configuration. Interface configuration determines the distribution of sensing (cyano unit) and displaying (EC unit) components. In a decentralised system, each EC unit is powered by a localised group of cyano units, reflecting on the photosynthetic activity of a specific region, thus making the system deconstructable and re-configurable. This allows for locally adaptive interfaces

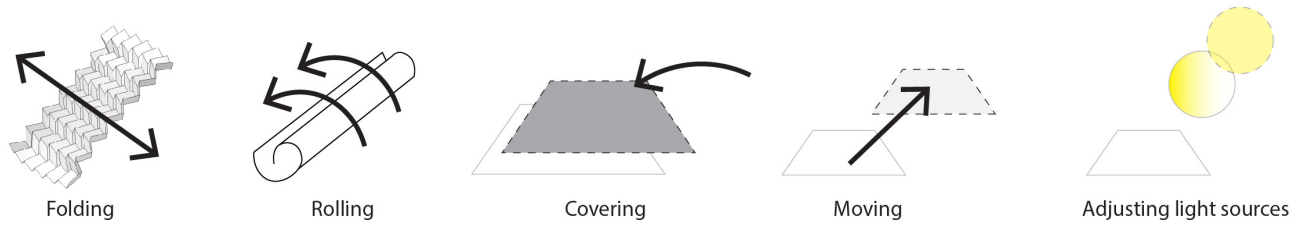

Figure 11: Possible actions that influences light conditions of the interface

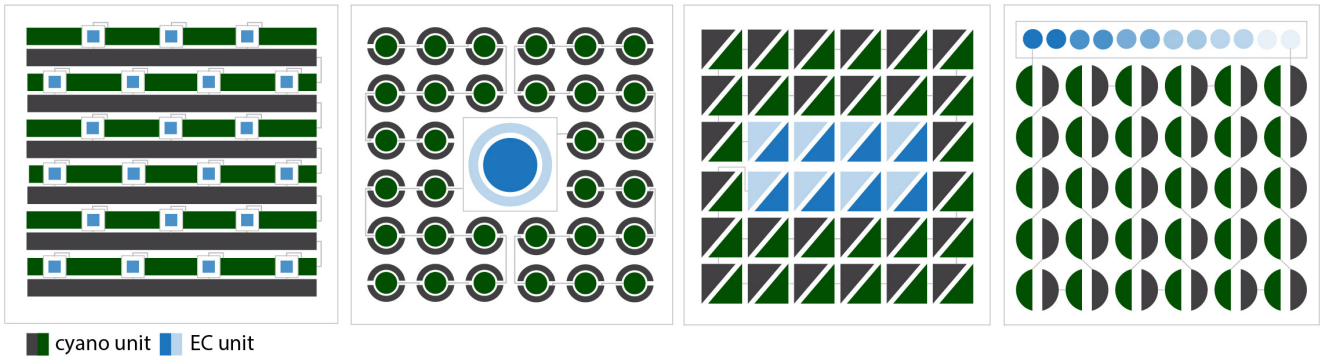

Figure 12: Coplanar Interface Variations. 1) striped parallels of Cyano units, with pixelated EC units, showing collective effects 2) circle patterned Cyano units, with an EC unit at the centre 3) triangular patterned Cyano units, with EC units at the centre 4) circle patterned Cyano units, with EC unit at the top, showing levelling-up effect

that can be customised to meet situational requirements, when uneven distribution of light needs to be indicated. In contrast, in a centralised system, the EC units reflect the overall photosynthetic activity of cyano units despite their respective locations.

4.2 Possible Actions to Influence Light Conditions

Due to the paperness of the interface, visually-triggered, light-adjusting interactions can happen in different ways (figure 11). In return, metabolism, and its resulting colour change of the interface, can be tuned. Possible actions include folding, rolling, covering, and moving, as well as adjusting light sources (such as drawing curtains, turning lights on and off). Amongst them, the first four are direct interactions with the paper substrate, and the last is an indirect interaction with the surrounding environment.

4.3 Interface Variations

Here we show four possible coplanar interface variations (figure 12), where design primitives are structured for diverse expressions. Primitives in these examples can be interchanged, multiplied and re-distributed for creative configurations; each interface can be multiplied and re-distributed, to allow for decentralised sensing and actuating. We will further elaborate how they could be tailored to function with four applications in the following section.

4.4 Application Concepts

This section outlines a selection of possible applications that integrates the interface as part of various design outcomes. Overall, we wanted the concepts to bring the interface to life: demonstrating potential implementations of its *temporal alignment capability*, through situating it within the realms of our everyday lives. More specifically, we envisioned how the possible outcomes of this timely noticing of microbes would look like in terms of fostering human-microbe interactions that are not only utilitarian, but also reciprocal. The concepts represent the Cyano-chromic Interface operating under a variety of situations based on different light sources, such as natural sunlight, artificial indoor light, and a combination of both. The concepts are briefly described below supported by renderings presented in realistic contexts.

4.4.1 Daylight Log. Human wellbeing is subject to natural daylight that is based around the rotation of the Earth. However, the change of daylight qualities in our living space is often unacknowledged. The Cyano-chromic Interface can respond to periodic fluctuations of (natural) daylight within its situated environment through noticeable colour change of the EC units. In *Daylight Log* (figure 13), at low light conditions, its EC units fade its colour, "requesting" humans to address the situation by unfolding the artefact that would expose the cells to more light (figure 13, middle). It reveals the miniscule shifts in light conditions within a matter of minutes, which provides a suitable time window, quick enough for delivering

Figure 13: *Daylight Log*: at low light conditions, its EC units fade its colour, "requesting" humans to address the situation by unfolding the artefact that would expose the cells to more light. The interface also allows the cyanobacteria to leave a visible trace for humans to notice and to reflect on their performances with the artefact over days, weeks, and beyond

Figure 14: *Kids' Hiking Companion*: Under intense sunlight, the Cyano-chromic Interface would blink faster, signalling for a break time and the need of cyanobacteria to be shaded. Within a few minutes of the break, the interface would slow down its blinking, thus reminding the hikers to continue with their trail

adequate care for the microbes but gradual enough to allow for being mindful of daylight range and fluctuations. The interface also allows the cyanobacteria to leave a visible trace [83][28], as a form of accumulated green biomass, for humans to notice and to reflect on their performances with the artefact over days, weeks, and beyond (figure 13, right). By doing so, humans allow themselves the opportunity to reflect and to celebrate their effort in long-term care for the microbes. This concept helps to imagine the design space where temporalities of the interface can be leveraged to suit multiple functions (e.g. timely care for microbes) and experiences (e.g. present and retrospective mindfulness), exposing the relations and multiplicity of temporalities [82].

4.4.2 Kids' Hiking Companion. Young hikers often overlook the importance of managing the timing and duration of breaks, which may lead them to over exercise. The *Kids' Hiking Companion* (figure 14) acts as a tunable timer that reminds the hikers to take regular short breaks, especially when hiking under intense sunlight. In that situation, the Cyano-chromic Interface would blink faster (figure 14, middle), signalling for a break time and the need for cyanobacteria to be shaded. Within a few minutes of the break, the interface would slow down its blinking (figure 14, right), thus reminding the hikers to continue with their trail. The interface could be positioned at body parts (e.g., upper chest) of the hiker, which would ensure sunlight exposure and adequate noticing by the wearer or their guardians. The concept addresses the needs of both the human and the cyanobacteria, allowing both to "pause" from their respective activities, whilst aligning their respective break times. It demonstrates the applicability of the interface for a variety of outdoor activities that would need various timely intervals of (collaborative) rest and recovery.

Figure 15: *Circadian Navigator*: As the cyano unit of the artefact reacts to the light emitted from the screen, the EC component would darken its colour which would subsequently restrict the opacity of the worn lenses (i.e., visibility), nudging the wearer away from their screen use.

Figure 16: *Mushroom Shade*: Under excessive sunlight, the EC unit of the interface would darken its colour, casting a protective shadow onto the fungi body underneath. Users can provide care to the mushrooms in a delicate way, by "planting" the Mushroom Shade above each cluster of fruiting bodies.

4.4.3 Circadian Navigator. Night time exposure to artificial light - such as those emitted by monitor screens of electronic devices - can disrupt human circadian rhythms, and could compromise our mood and sleep quality. Interestingly, such night time exposure to artificial light can also disturb circadian rhythms of cyanobacteria [16]. As an artefact to be worn around the eyes, *Circadian Navigator* (figure 15) invites users to undertake a shared journey with the navigating microbes, as a way of embracing darkness together and collaboratively steering away from screen use. As the cyano unit of the artefact reacts to the light emitted from the screen, the EC component would darken its colour which would subsequently restrict the opacity of the worn lenses (i.e., visibility) (figure 15, middle), nudging the wearer away from their screen use. The artefact illustrates the potential of Cyano-chromic Interface towards facilitating healthy night practices; minimising night time artificial light engagement and thus aiding better (human) mood and higher quality rest.

4.4.4 Mushroom Shade. As part of the domestic food-web, growing and harvesting mushrooms at home helps in reusing food waste, towards self-sustainable and localised food production endeavours. The mushrooms usually need a moderate light environment for healthy growth, and should avoid direct sunlight. *Mushroom Shade* (figure 16) explores the Cyano-chromic Interface's ability to provide a chromatic "shield", designed to regulate light conditions for the mushrooms. Under excessive sunlight, the EC unit of the interface would darken its colour, casting a protective shadow onto the fungi body underneath (figure 16, right). By such visual signalling, the interface also aids to communicate environmental light changes to humans. As such, users can provide care to the mushrooms in a delicate way, by "planting" the *Mushroom Shade* above each cluster of fruiting bodies (figure 16, middle), or moving both species to a more shaded place. The Mushroom Shade illustrates the potential of Cyano-chromic Interface in engaging users in noticing not only cyanobacteria, but also the growth of food-producing fungi, thus carefully managing light and shadows that nourishes both microbial species.

5 DISCUSSION

With their unique abilities to sense and adapt to environmental stimuli, microbes offer a wide range of possibilities for design and HCI. However, living with microbial living artefacts often faces the challenge of temporal dissonance that hinders timely notice and fluency of interaction. We introduced the Cyano-chromic Interface, as one way to address such a challenge by aligning temporalities between humans and microbes. The interface is designed to respond to photosynthetic activities of cyanobacteria (influenced by environmental light conditions) with reduced time lag, by changing its colour and intensity at a rate that can be made more noticeable to humans, through an electrochromic (EC) component. We showed that the Cyano-chromic Interface effectively surfaced cyanobacteria's metabolism (photosynthesis) and speculated on the situations in which artefacts designed based on the interface can help enable reciprocal relationships of humans and cyanobacteria and engage humans to connect and empathise with other nonhuman species. We begin to unpack the functional and experiential aspects of the interface, followed by other potentials in extending design spaces for biological-HCI.

5.1 Towards Timely Noticing and Care for Microbes

On an experiential level, the reduction in time taken to notice photosynthetic activities of cyanobacteria, as technically demonstrated by the Cyano-chromic Interface, opens up a pathway towards experiencing living artefacts that are more responsive to human and environmental inputs. In other words, the interface is a technically eloquent way to placate the so-called "slowness of biology" that has been framed as a design challenge by some HCI scholars (e.g., [55], p.266; [54] p.221; [78] p.2211, [2]; [56] p.3, etc.). At the same time, however, thanks to the cyano unit, the interface preserves the inherent temporality of the microbe, as something that can facilitate and encourage slow interactions; a research topic that has been ongoingly explored in HCI (e.g., [74][50]; [7]p.2). In other words, designers may also consider the interface towards creating slow artefacts towards reflection, contemplation, and patience: Over the course of days and weeks, with healthy (and patient) management of cells, users of the Cyano-chromic Interface would notice an increase in intensity of green hues from the interface, resulting from the accumulation of chlorophyll. This ability of the interface to also visually express photosynthetic wellbeing of microbes over wider time-spans - here in the ranges of *days/weeks* - users of the artefacts are given time to reflect and to contemplate on their past relationship in looking after their microbes.

On a functional level, our Cyano-chromic Interface can be framed as a vital component in supporting designs that would enable microbial *noticing* [92][60] and *surfacing livingness* [49] that can lead towards delivery of *care* [19] and the design of *mutualistic care* [42]. Our proposed applications have emphasised the type of care that is concerned with maintaining the health of cyanobacteria. Taking a remedial and ecological stance towards application of biotechnology, we concur with other HCI scholars (e.g., [3][12][4][22]) in arguing that one of the most pressing areas for application of the living interface, should be targeted towards empathising and caring for living beings. Not only for the integrated cyanobacteria themselves, but also for mutualistic relationships between living artefacts and humans, and for other non-human species that make up the diverse ecological assemblages. Moving forward, our proposed applications illustrate several possible ways to solicit care. Several mechanics inherent in Cyano-chromic Interface's operation have been leveraged from the users of our imaginary living artefacts. From its pronounced colour fading in *Daylight Log*, to a blinkable display in *Kids' Hiking Companion*, and the light responsive darkening involved in *Circadian Navigator*, the interface offers choice and adjustability with which designers can implement in eliciting care according to different situations, and multiple species involved in them (showcased by *Mushroom Shade*).

5.2 Interface Paperness and its Performative Potential

The material attributes of the interface suggests a tangible and interactive way of designing microbial interfaces. As demonstrated from experiment results, the printed coplanar configuration can accommodate the cyano unit of the Cyano-chromic Interface to be 3D-printed in sequence onto paper substrates. This enables *multi-situatedness* [44] of the interface to be applied in various types of artefacts and situated in diverse contexts, as demonstrated by the diversity of proposed applications. With this we suggest that Cyano-chromic Interface can be a paper-based composite - a type of hybrid material which has been explored in HCI previously for many types of computational composites [93]: e.g., in supporting tangible interactions [96], sensing and actuating [94] [77], generating energy [18] and crafting circuits[70].

As a design material, paper is simple and affordable, whilst offering craft characteristics to technology[70]. Its inherent qualities, e.g., lightweight, flexible, air/water-permeable, rough, porous and absorbent, affords diverse actions [94] both in fabrication time (e.g., print, paint, fold, cut, and glue) and use time (e.g., fold and roll). Due to its porosity and absorbency, print-ability of paper has been widely applied in hosting conductive inks and polymers (e.g., [94][96][77][70]). In the Cyano-chromic Interface, wet and nutrition-diffused watercolour paper provided bio-receptibility to living cyanobacteria cells. The stiffness and robustness of the paper used, allows repeatable folding and unfolding. Based on this, we designed and incorporated folding interactions in *Daylight Log* to alter light and shade projected onto the cyanobacteria. If designers want to further increase such *performative* potential of the interface rooted in its material qualities [26] [45], we suggest exploring various origami [52][57][90] or kirigami techniques [46][40][97], which allows multi-dimensional foldings and stretchings to be integrated into interactions with the microbe. This could make the interface more intuitive in eliciting actions from people towards novel configurations and care practices in the everyday.

5.3 Tunable Interface Towards Diversity of Outcomes

As we analyse design primitives of our Cyano-chromic Interface, we suggest a further potential offered by the interface, that of enabling designers the possibility to tune the performance of living artefacts. Given its inherent modularity and small size as a building block, the interface helps with calibration of design outcomes through

iterative processes of adding, subtracting, and re-distributing. Some designs may require a large surface area to display colour change, whilst some situations may call for its reduction, depending on the needs of its user(s). Surface area of *Daylight Log*, for example, may need adjusting to address varied individual domestic environments within which the living artefact would be situated. Similarly, high diversity of mushrooms would rely on *Mushroom Shade*'s adjustability to cater for the density and species-specific needs of the fungi.

In addition, configurations of the Cyano-chromic Interface suggest that its tunability may also arise from multiplication and distribution of its constituting design primitives. For example, by adopting either a centralised or decentralised system (as shown in Design Space), the interface can be used to indicate photosynthetic activity of cyanobacteria in two different ways. A centralised system can be applied in scenarios where the holistic activity of a living artefact needs to be noticed and acted upon. In *Kids' Hiking Companion* for example, EC units indicate overall sun exposure. Localised sensing enabled by a decentralised system is more meaningful in indicating location-relevant "data" of state changes, in a similar way to how meta-materials are applied in sensing local environmental stimuli [86][72]. In short, instead of signalling chemicals [86] or mechanical pressures [72], the decentralised interface would provide opportunities in sensing and responding to regional light differences. A tunable Cyano-chromic Interface would, in essence, empower designers with diversity of processes and outcomes. Tuning living artefacts may thus extend its accessibility to cater for, and to address the diverse requirements of its human and non-human participants.

5.4 Lessons Learned

In this reflexive part of the discussion, we identify lessons regarding research methodology and outcomes, which we learned during the development of our Cyano-chromic Interface. We conclude with a set of recommendations that designers, operating at the intersection between design and biology, could consider and implement for designing living artefacts.

5.4.1 Addressing Balance Between Imaginaries and Scientific Grounding. Back and forth thinking between experiments and design conceptualization has been a common practice in material-driven and making practices in design and HCI [43][21], and more recently adopted by Bio-HCI (e.g., [28]). For our research, we had also adopted such an approach. On one hand, experiments helped us to better gauge the range of temporalities offered by the EC unit. Meanwhile, design thinking helped us to dig deeper into the semantics of our empirical findings in the context of the everyday. We suggest researchers, in case of technical hurdles, keep a holistic view on research goals which helps in better managing priorities given limited time of projects. We encourage the HCI community to explore and to strike a balance in the spectrum between epistemologically unlimited imaginaries and scientific grounding.

5.4.2 Tacit Knowledge in Biodesign. We had encountered a few protocols that required what some might call "tacit knowledge", a type of information or skill that is difficult to obtain or apply without first-hand experience. Although scientific literature can often provide step by step guides for certain experimental procedures, tacit knowledge, which may be critical in successful reproduction of a method, would not be obtained. For instance, when we were developing the cyano unit, we followed a published protocol, in which one of the steps had been omitted . We suspect that this may be due to the fact that its authors may perceive the step to be too trivial to be included in the publication. As we tried to replicate the published experiment and tailor it for our design, the protocol could not be reproduced; meaning that further time was spent on troubleshooting through trial and error, whilst attempting to obtain clarification directly from the protocol authors.

Reflecting on tacit knowledge not articulated by ourselves, we also found it difficult to describe all details of the making of our interface in this paper. This was most evident during the development of the EC unit. In particular, the screen printing technique required to imprint the electrochromic pigment was difficult to execute, by simply following its retailer's written instructions alone. It was only through a series of trial and error, and consultation with an experienced colleague that resolved the issue - a time consuming process that we could have anticipated, and a lesson that we invite others to learn from.

For this reason we propose that the HCI community should, 1) ensure transparency and repeatability when publishing research methods, and be more explicit on technical details when providing supplementary materials, 2) establish better communication channels between researchers, and 3) take extra care when connecting with potential collaborators. We also suggest HCI researchers establish strong collaborations with organism-specific experts at an early stage of the research, to ensure validity of methods and outcomes.

5.4.3 Strategizing Lab and Studio Usage. We have found it efficient to strategize the use of two contrasting working environments: laboratory and "design studio" (in our case, a home studio), when working with living organisms. Designing and experimenting with microorganisms requires strict protocols and maintenance schedules (see, e.g., [76][28]). It often requires a biosafety level 1 biolab, which allows working with well-characterised agents which do not cause disease in humans. However, not all stages of the project need such regulated set-up. As the first author reflects on the start of the "Cyano-chromic Interface journey"; which involved living with and observing microbes outside of a lab. Here, using substitute laboratory resources suffice for culture maintenance (e.g., using glassware to replace laboratory flasks). Further still, a commercially accessible species of the cyanobacterium *Spirulina* platensis was chosen in place of *Synechocystis* sp. PCC 6803. In a similar way, we modified a 3D printer for bio-printing and custom-made a sterile cabin for the 3D printer at a prototyping workshop. With the commonly observed problem of limited lab access, we thus suggest designers to critically assess their particular requirements before constructing a plan of action, as a way to maximise efficiency of resource usage between the laboratory and the design studio. Furthermore, we suggest that more open approaches to understand and attune to microbes we design with, such as sensitizing with them at casual settings (e.g., home or design studio), are worth attention in the bio-HCI community. They could offer creative spaces for designers and researchers to engage with microbes in various ways and lead to rich and personal interpretations of microbial phenomena.

5.5 Limitations and Future Work

5.5.1 Beyond Light and EC. Light has been explored for Cyano-chromic Interface as an environmental stimulus. However, we recognize that other factors, such as temperature and humidity, would also affect photosynthetic activity of the organism [53]. To that end, with this study, we could only scratch the surface of what could be done with Cyano-chromic Interface. However, focusing on one factor as a stimulus helps with technical implementation and provides initial insights for studying other factors. In our future work, we aim to explore the effects of other stimuli and other technologies for surfacing livingness (e.g., shape changing materials) and their interrelations to inspire other types of living interfaces in HCI. For example, using soft, flexible and transparent materials as surfacing technologies could enhance the life-like qualities of the interface towards more organic forms.

5.5.2 In-Situ Explorations. We regard our interfaces as speculations towards generating potential imaginaries of how the Cyano-chromic Interface might be used in social and cultural contexts. We would like to further explore their care and performative potentials through empirical user studies that situate the interface in the everyday. This would require longitudinal studies (lasting between one to three months), which will present challenges of long-term maintenance of microbial viability. For example, we expect dehydration and increased risk of contamination during long-term operation of our interfaces - factors that also need careful management by the users. Furthermore, the interface might need to be presented with complementary guidelines to make this technology understandable by users. We aim to touch upon such practical challenges in our next iteration. To this end, despite its potential, questions of its performance in the wild are yet to be answered. Nevertheless, we are confident in the realisation of these interfaces in future design iterations.

5.5.3 Instrumentalisation and Moving Forward. Instrumentalisation can be an inevitable challenge in dealing with human-nonhuman relations [61] in biodesign. We recognize a certain level of *instrumentalisation* [61] of microbes in the Cyano-chromic Interface and proposed applications. For instance, habituating living cells in a hydrogel is an unnatural act that removes the microbes away from their natural environments. This could have consequences to their wellbeing that cannot yet be fully anticipated. To mitigate this tension, for our future research, exploring open and less "human-intended/intervened" interfaces could be considered as a starting point. One example of this is a concept named *Flavo in Situ* [49], which invites natural interactions of multiple organisms in a semi-natural habitat and an ecosystem. However, how such an open approach could be integrated in endeavours of temporal alignment is yet to be explored.

5.5.4 Sustainability of the Cyano-chromic Interface. Cyanobacteria are able to absorb carbon dioxide from the atmosphere and release oxygen, a process that is thought to contribute significantly to the global carbon cycle. However, designing an artificial habitat for them by default, is not necessarily climate-friendly. Experimenting and prototyping require products, chemicals, and materials that might not be sustainably produced, distributed, and disposed of. For instance, in our case, to harness the electrons from the organism, we used off-the-shelf conductive ink and electrical wires, which does not make the interface purely bio-based and regenerative. Lab experiments also generate a lot of disposables. Although one of the motivations behind microbial interfaces are for sustainability transition of the HCI field and ultimately the betterment of human-microbe relations, when it comes to practical implication of such interfaces, there is usually a trade-off between the desired effect and its environmental impact. Designers should be critical about the level of engineering involved to reach their goal. In our case, we reflect on our prototypes, whilst acknowledging that there is substantial room to analyse and to potentially improve on the environmental impact of the design, which is one of our future research endeavours.

6 CONCLUSION

This paper introduces "Cyano-chromic Interface", designed to address the challenge of temporal dissonance between humans and microbes in living artefacts. Consisting of cyanobacteria and an electrochromic (EC) material, the interface helps to timely surface photosynthetic activity of the microbe. Grounding through a technical study of the interface performance, we illustrated its design primitives, which further inspired the development of application concepts. Through this we instantiate how the interface can be tuned for diverse functional and experiential outcomes in living artefacts; for instance, towards eliciting timely care and inviting continual reflections. We invite the HCI community to further explore technologically-mediated designs for aligning multiple temporalities, towards fostering sustainable relations between humans, microbes, and beyond.

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A APPENDIX

A.1 The construction of the Cyano-chromic Interface

In this section, we outline the multiple steps that were taken in the construction of our Cyano-chromic Interface, highlighting the multidisciplinary nature of our design processes. We begin by explaining how the cyanobacteria cells were cultured and maintained, followed by how the microbes were integrated as part of the interface fabrication process, involving custom modification of 3D printing machinery. We conclude the section with its assembly steps.

A.1.1 Culturing and Maintaining Cyanobacteria. *Synechocystis* sp. PCC 6803 cells (Pasteur Culture Collection, France) were cultured in BG-11 medium (pH 7) with trace metal mix solution (Sigma-Aldrich). Cultures were maintained in a biosafety level 1 lab, under a light/dark cycle of 12:12h and an illumination level of approximately 10 μmol $\cdot$ $m^{-2} \cdot s^{-1}$, with a white LED light, in a sterile environment (figure 17).

A.1.2 Fabricating Interface Components. Interface fabrication was based around the Direct Ink Writing (DIW), an extrusion-based additive manufacturing method, which generally enables custom design configurations of electrodes towards achieving optimal power output. More specifically, we made an additional improvement to an existing method of ink-jet printed paper-based biophotovoltaic (BPV) system [84], a technique that has shown to reduce bulkiness of traditional liquid-reservoir based systems. Here, we used DIW [87] for depositing conductive inks and cyanobacterial culture in the form of bio-ink in our interface, which retains the benefit of ink-jet printing (reducing bulkiness), but also has other advantages. In this method the cyanobacteria become immobilised in hydrogel during the printing process for retaining moisture over a longer period. It also allows for the printing of a wider range of inks of various particle size and viscosity.

1) (Bio)printing. First, anode ink (suspended solution of carbon nanotubes, Nink1000 ink from Nano-lab USA) and cathode ink (Carbon-platinum Uno-ink from FuelCellEarth, USA) were printed onto a piece of copy paper ($80g/m^2$) in sequence, with a modified 3D printer (Creality Ender Pro 3). The inks were loaded onto a syringe with a piston, which was controlled by a modified extruder. Desired patterns with different shapes and sizes were designed and converted into g-codes for the printer to read and execute. The syringe was connected to a print nozzle (OD = 0.97mm) via silicone tubing (ID = 4mm; OD = 6mm). The paper was pasted onto the print bed using a low-tack tape to prevent warping of the paper during printing. An extrusion rate of 3 mL/h was maintained throughout the process of ink printing.

Second, bio-ink containing the cyanobacteria culture was printed onto the anode. The printing needed to be processed within a sterile environment. As such, we designed and constructed a sterile bio-printing cabin for housing the 3D printer and the printing process.

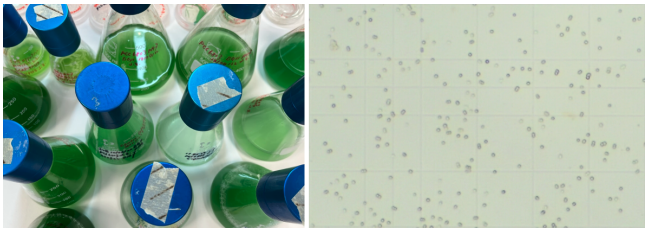

Figure 17: *Synechocystis* sp. PCC6803 liquid culture grown for 4-6 weeks (left) and a microscopic image of the cells (100x magnitude) (right)

Here, we dismounted the hot-end module and replaced it with a liquid extrusion unit consisting of a syringe, a syringe pump, silicone tubing, and a tube holder. Figure 18 illustrates the overall set up, with its different components and functions. The bio-ink was made using a concentrated pellet of cyanobacteria, which was obtained by centrifuging 50 mL of a 4-6 week old *Synechocystis* sp. PCC 6803 culture (spun at 4000 rpm for 5 mins). The concentrated pellet was then resuspended in 5 mL of fresh BG-11 medium. 5 ml of sodium alginate (5 w/v%) was added to the suspension and vortexed as the final step in the bio-ink preparation. Concentration of cyanobacteria cells in this final bio-ink preparation, was measured (using Fuji ImageJ) as $5.65x10^8 cells/ml$. An ink-loaded anode paper was pasted over the top of the low tack tape on an acrylic plate, and supplied with 1 drop of calcium chloride (5M). The surface of the ink-loaded paper was flattened with an L-shaped spreader.

Bioprinting was performed using the same modified 3D printer (Creality Ender Pro 3) in our customised sterile cabin. A sterile syringe was loaded with 10 mL of bio-ink and mounted onto a syringe pump. The syringe was connected to a 0.2 mL pipette tip via silicone tubing (ID = 4mm; OD = 6mm). An extrusion rate of 14 mL/h was maintained throughout the printing process.

2) Electrochromic (EC) Material Preparation. The electrochromic material was made by screen-printing PEDOT:PSS pigment in-between two sheets of ITO coated PET. We followed the instructions shared by Ynvisible, the company that developed the EC material which we used [37].

A.1.3 Assembly of a Stacked Cyano Unit. To assemble the stacked cyano unit, the following components were prepared: 2 pieces of square stainless steel plates (65 x 65 mm), 1 piece of acrylics (65 x 65 mm), 2 pieces of hydrogel sheets (40 x 40 mm), plastic screws, connecting wires, cathode material and printed anode material. Figure 19 illustrates the stacked cyano unit assembly process. In this configuration we used off-the-shelf carbon paper loaded with Platinum (purchased from H2Planet Europe) as an alternative for the cathode ink, to simplify the characterization process.

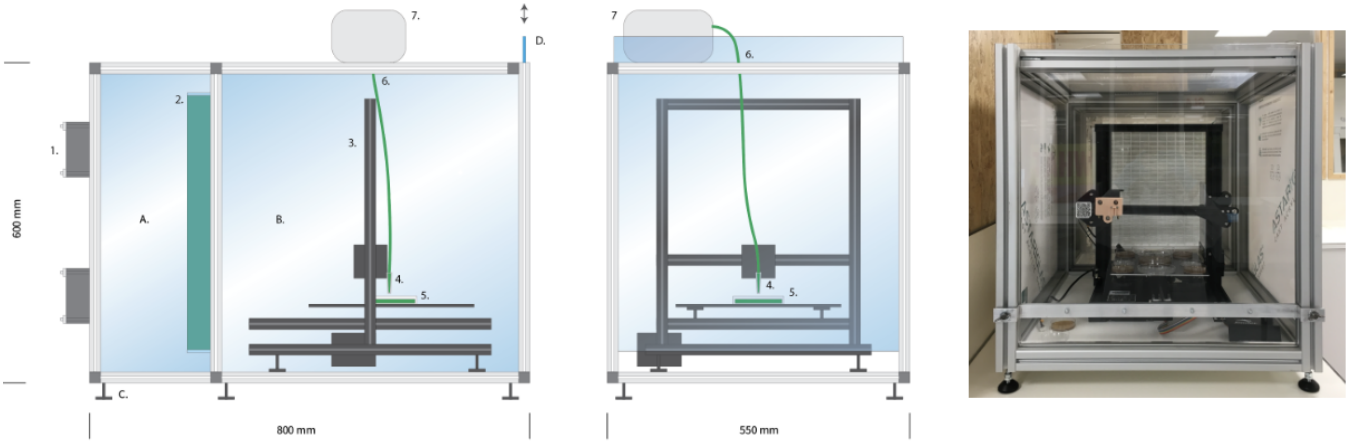

Figure 18: Printer cabin design illustration and photograph of the set-up. Main sections: A. back chamber for HEPA filter B. front chamber for printing C. adjustable feet for levelling D. sliding window for ventilation and operation. Components: 1. Fans for blowing air into the chamber 2. HEPA filter for catching particles from air flow 3. 3D printer 4. Printing nozzle adapted from a D10 pipette tip 5. Plate for print substrate 6. Hole for tubing 7. A syringe pump (details not shown)

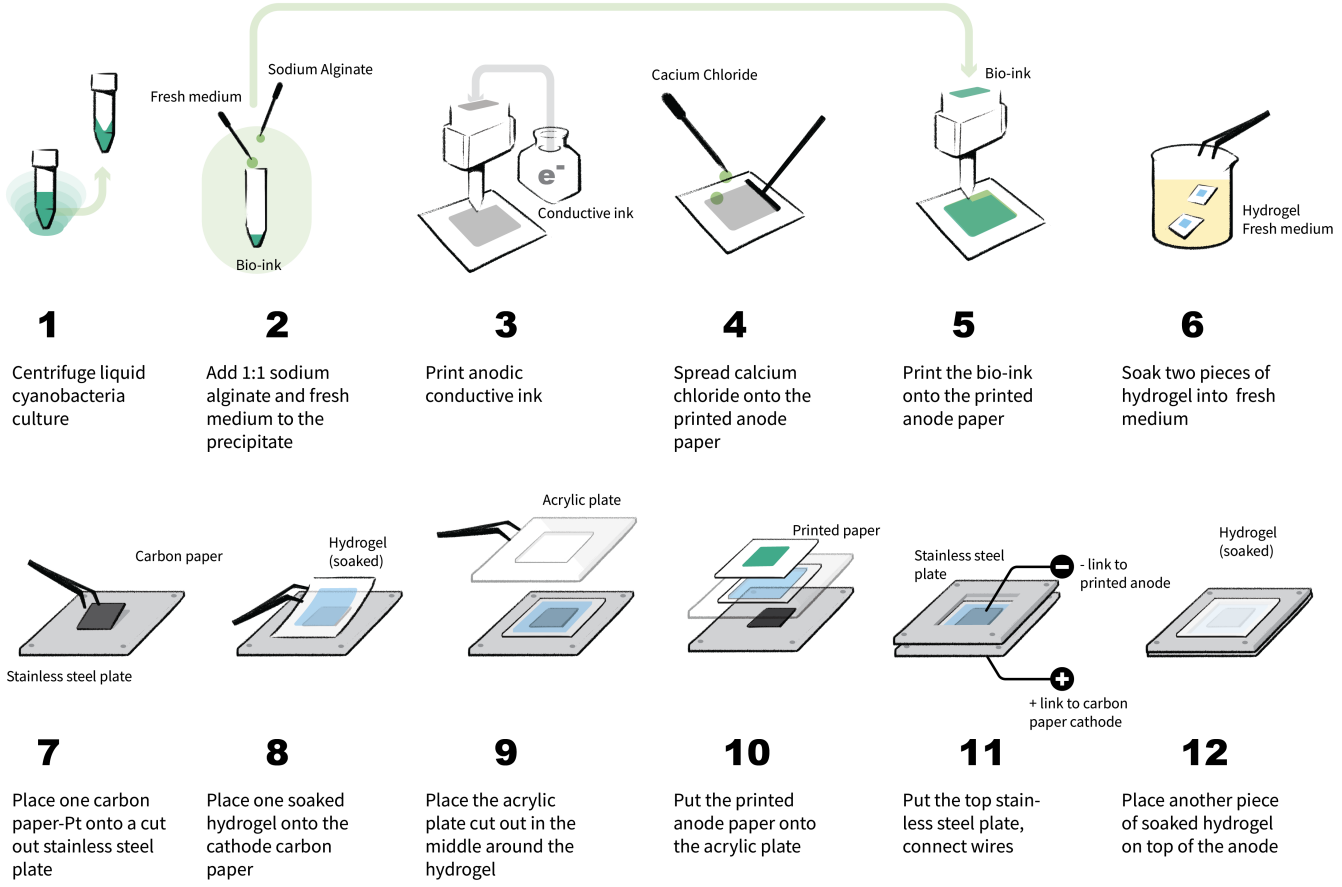

Figure 19: Steps involved in stacked cyano unit assembly.