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Groutars, Eduard Georges; Risseeuw, C.C.; Ingham, Colin; Hamidjaja, Raditijo; Elkhuizen, Willemijn S.; Pont, Sylvia C.; Karana, Elvin

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Flavorium: An Exploration of Flavobacteria's Living Aesthetics for Living Color Interfaces

E.G. Groutars[*†]
Avans University of Applied Sciences
Breda, The Netherlands
wardgroutars@gmail.com

C.C. Risseeuw[*‡]
Delft University of Technology
Delft, The Netherlands
C.C.Risseeuw@tudelft.nl

C.J. Ingham
R. Hamidjaja
Hoekmine BV
Utrecht, The Netherlands
hoekmine@gmail.com

W.S. Elkhuizen
S.C. Pont
Delft University of Technology
Delft, The Netherlands
W.S.Elkhuizen@tudelft.nl
S.C.Pont@tudelft.nl

E. Karana[§]
Delft University of Technology
Delft, The Netherlands
E.Karana@tudelft.nl

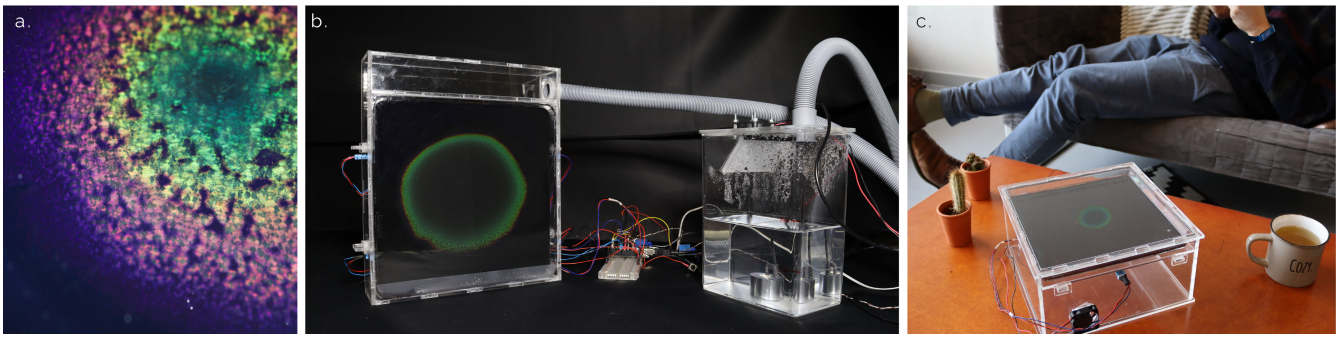

Figure 1: Flavobacteria as a medium for Living Color Interfaces (LCIs). (a) Vivid colorations produced by Flavobacteria. (b) Flavorium, a bio-digital artifact for Flavobacteria to thrive for a month. (c) A LCI with Flavobacteria embodying users' physical activity measured by a smartwatch.

ABSTRACT

Flavobacteria, which can be found in marine environments, are able to grow in highly organized colonies producing vivid iridescent colorations. While much is known about the biology of these organisms, their design potential as responsive media in user interfaces has not been explored. Our paper aims at bridging this gap by providing insights into the type, degree, and duration of change in Flavobacteria's expression, i.e., their living aesthetics. We present a tool to capture and characterize these changes concerning form, texture and iridescent color. To support the long-term study of their living aesthetics, we designed Flavorium. This bio-digital artifact provides the necessary habitat conditions for Flavobacteria to thrive for a month. Granting insights into the responsive behavior of this organism, this work presents a design space, vocabulary, and application concepts to inspire HCI and design scholars to investigate the complex temporal qualities of living media for future user interfaces.

CCS CONCEPTS

• **Human-centered computing → Interactive systems and tools**.

KEYWORDS

Biological HCI, Living Media Interfaces, Living Aesthetics, Iridescent Color, Flavobacteria

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[*]Both authors contributed equally to this research.
[†]Also with Delft University of Technology.
[‡]Also with Avans University of Applied Sciences.
[§]Also with Avans University of Applied Sciences.

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1 INTRODUCTION

The integration of living organisms into interactive systems is a growing area of interest for HCI and design researchers [12, 27–29, 53, 65, 68, 74, 76, 77]. Organisms have, for example, been embedded in interactive installations [1, 58, 59], hybrid computer games [54, 55, 80], wearables [61, 97] and interface designs [5, 13, 14, 22, 32, 35], in which novel functionalities and interaction possibilities are achieved through substitution of computer input and output with living media. Within this body of work, some have proposed conceptual frameworks informing the HCI community on the challenges and opportunities that arise when working with living organisms [65, 77].

In parallel, a body of research in the HCI community brings to attention the social dimension of living media [13, 15, 60, 85]. For example, researchers discussed the roles living organisms could play in new ways of living and working at home [28] while raising critical questions about temporality, care, symbiosis, and cohabitation [5, 44, 71]. In line with this body of work, foregrounding livingness as a biological, ecological, and experiential phenomenon, Karana et al. [44] proposed the concept of living aesthetics, i.e., the way humans experience the type, degree, and duration of change in a living artefact that occurs due to the growth, reproduction and death of an organism. In particular, we are inspired by the unique living aesthetics of Flavobacteria, which infers them as a potential medium for future Living Color Interfaces (LCIs).

The ability of living organisms to dynamically change the color of an artefact has been harnessed in diverse ways in HCI and design, for example, through pigment producing bacteria [62, 86], fluorescent bacteria [14, 61] or bioluminescent algae [5, 71]. Flavobacteria can add to this repertoire by changing the color of an artifact through their structural color. These bacteria, which can be found in marine environments, are able to grow as part of a densely organized colony. Through this multicellular organization, they form photonic crystals which reflect light in specific ways, creating striking visual effects [38]. Whilst the term 'photonic crystal' may be unfamiliar to many, the effects of this form of structural color are not. The underlying optical mechanism is similar to that of the peacock's bright feathers which produce color through naturally formed nanostructures rather than pigments. Microbiologists have researched Flavobacteria's ability to self-organize in relation to various abiotic factors (i.e., non-living chemical and physical parts of the environment that affect living organisms) [51], the presence of other microbes [33] and the underlying genetic pathways [38]. However, despite their vivid colorations and highly responsive behavior, Flavobacteria are yet to be explored as a living medium for human-computer interaction design.

This research contributes to the ongoing work in Biological HCI [28, 53, 65, 76, 77], expanding the scope and design opportunities with the introduction of Flavobacteria as a medium for Living Color Interfaces (Figure 1). Specifically, our goal is to study Flavobacteria's aesthetics over time, and how these can be tuned with different input mechanisms. Capturing and characterizing Flavobacteria's living aesthetics is intriguing but not straightforward due to their angle-dependent and temporal color that varies across the growing colony. This dynamic complexity requires a unique research approach that combines knowledge, tools and techniques from microbiology, vision and imaging sciences, and design. Informed by the iterations between these knowledge domains, combining systematic lab experiments and design explorations, this work presents the following:

- Design space introducing a variety of input mechanisms that influence Flavobacteria's living color output (i.e., their living aesthetics),
- Vocabulary to analyze and communicate Flavobacteria's living aesthetics as well as a tool to capture and characterize these,
- First insights on how living aesthetics of Flavobacteria are tuned with a specific input mechanism (i.e., humidity), presented with rich data illustrating changes in form, texture and iridescent color over seven days,
- Flavorium, a bio-digital artifact, which provides the necessary habitat for Flavobacteria to thrive for a longer time (at least a month), opening up new possibilities for long-term studying of Flavobacteria's behavior for Living Color Interfaces (LCIs),
- Application concepts proposing diverse potentials of Flavobacteria-based LCIs for HCI.

2 RELATED WORK

2.1 Color Changing Interfaces in HCI

Over the last decades, we have seen growing interest among HCI and design researchers in the application of physical materials as an alternative to digital screens for interacting with computational systems [21, 36, 37]. Such physical user interfaces can potentially provide for rich multisensory experiences in everyday interactions that go beyond the capabilities of traditional graphical user interfaces. Within this field of physical user interfaces [34, 67, 75, 99], materials with the ability to change their color are especially of interest for the scope of this paper. In HCI, researchers proposed thermochromic materials that change their color in relation to temperature as a basis for interactive fabrics [96] and make-up [42], enabling wearers to seamlessly alter their appearance in more *abstract, ambient* and *ambiguous* manners than screen-based displays [17]. Also explored for novel user interfaces are electro-luminescent materials that change their color in relation to an electrical current [4, 41] and photochromic materials, that allow for the coloring and recoloring of objects using certain wavelengths of light [78] and the intentional degradation of stains on textiles [8]. Nilsson et al. [70] experimented with the patterns of color change in the textile upholstery on an interactive piece of furniture. Given the dynamic nature of such color changing interfaces, Tsuji and Wakita [39] have shown interest in understanding the aesthetics of their temporal appearance, for example, for the colors inside Japanese calligraphy. We aim to develop such an understanding for a color changing interface using the emergent properties of living bacteria.

2.2 Biological HCI

Recent years have seen multiple HCI projects that focus on integrating living organisms as design elements, bringing forth novel

interaction possibilities between humans, computers and biological systems [53, 65, 74, 76, 77]. In these projects, bacteria [1, 14], fungi [13, 32], algae [5, 71] and even quasi living viruses [52] have been proposed as design elements. Hamidi and Baljko [32] developed a fungus-based interface, where data about the usage of a digital app is visualized through the growth of the fruiting bodies of fungi. In a similar manner, bioluminescent bacteria have been used to visualize social network activity [14]. These examples highlight how living organisms can act as the actuator in interactive systems, displaying information in an ambient manner. Living organisms can also fulfill the role of a sensor, as proposed in the Living Tattoo project where Liu et al. [61] developed a wearable containing transgenic bacteria, able to respond to chemical stimuli by producing fluorescent proteins.

In consonance with such developments, researchers have proposed frameworks and practical guidelines for the integration of living organisms in HCI [44, 65, 74, 76, 77]. This is an effort to consolidate the different fields of expertise involved and to highlight various opportunities, challenges and ethical dilemmas that come into play. Interviewing bio artists, community lab organizers and DIYbio researchers, Asgarali-Hoffman and Hamidi [2] grant insights on such opportunities and challenges at the intersection of bioart and HCI. Kuznetsov et al. [57] discuss how a design studio can be transformed into a biosafety level 1 laboratory, engaging HCI researchers in exploring biomaterials. Inspired by Tangible Bits [37] and challenging traditional boundaries between biological cells and computers, Pataranutaporn et al. [77] proposed the concept of Living Bits, a framework to support *characterization of human-microbe interactions across contexts and scales.* Merritt et al. [65] proposed Living Media Interfaces (LMIs) as interfaces that "incorporate living organisms and biological materials, taking advantage of their qualities to enable different forms of interaction between humans and digital systems". Grounded in an overview of the current design space, their research brings to the attention the *Biological, Ethical, Artistic,* and *HCI* perspectives to be considered in the design of LMIs.

Our work contributes to this line of work in HCI by proposing Living Color Interfaces (LCIs) as a form of Living Media Interfaces [65], emphasizing the ability of organisms to produce color which changes over time and in response to the environment and user. Bringing attention to changes that occur in living artefacts during their use time (e.g., color changes) due to the growth, reproduction and death of a living organism, Karana et al. [44] proposed *living aesthetics* as one of the fundamental principles of designing for livingness in Biodesign.

2.3 Living Aesthetics

The dynamic and temporal qualities of materials have been reflected in diverse literature crossing HCI and interaction design [4, 10, 64, 81, 82, 91, 92]. Parkes and Ishii [75] brought to attention the need for a vocabulary to express behavioral transformability in shape changing materials. Concepts such as becoming materials [98] and temporal form [92] have been put forward, referring to the temporal capacity of computational materials to assume multiple aesthetic expressions that unfold only over time and in context. In line with this body of work, Döring et al. [21] introduced the concept of Ephemeral User Interfaces, intentionally created to last for a limited time and typically incorporate materials that evoke a rich and multisensory experiences like water [20], ice [93] and soap bubbles [90]. Karana et al. [44] suggest a similar understanding of living materials as dynamic and temporal, open to change at both design and use time. These studies on computational and biological materials alike suggest that in designing with new materials, we need to re-evaluate the ways in which we understand the reaction times and manners in responsive media, as well as the modes of interaction [47, 92].

The notion of living aesthetics provides a theoretical understanding of temporality in living artefacts [44]. It brings the focus to the social dimension of living artefacts, calling for a purposeful design of change from the initial state of a living material to the end of its life, indicating how aspects of livingness (i.e., growth, reproduction and death) come to expression in the artefact, and can, therefore, be experienced. Through diverse practical examples, the researchers illustrate how designers navigate between the different dimensions of living aesthetics (e.g., immediate or gradual changes in color, form, or function). Synthesizing the concepts Ephemeral User Interfaces [21] and Living Media interfaces [65], Barati et al. [5] introduced Living Light Interfaces in exploring the living and short-lived expressions of bioluminescent algae, i.e., their living aesthetics [44]. In this specific example, the researchers illustrated how the flash characteristics of dinoflagellates in a liquid culture change under a range of kinetic stimuli, including orbital rotation, pulsation and vibration. The *living light aesthetics* are presented as the intensity variations over time, textural qualities and spatial distribution [5].

Inspired by this body of work in HCI, we aim, in this paper, to provide an initial understanding of the living aesthetics of Flavobacteria, concerning the relation between diverse stimuli (e.g., humidity) and the quality of their living color. Color is an important element in biodesign to communicate through living media [27, 68]. For example, Smith et al. [86] embedded pigment producing bacteria in additively manufactured masks named Vespers, to enable a predefined and gradual color change over time. While the color change in Vespers is achieved through chemically induced behavior of genetically engineered bacteria, we can also identify projects in which such a level of control is not favored. For example, in the creation of a living billboard, advertising the Contagion movie in 2011, designers cultivated multiple organisms in a giant Petri dish, providing a dramatic change of color and texture over time and emphasizing the agency of organisms themselves [72].

These works showcase the capacity of biological systems to change the color of an artifact, whether this is controlled by humans, left to the agency of the organisms, or through a collaborative effort between humans and other living organisms. This foregrounds the need for a more extensive elaboration on how the livingness of living media come to expression in LCIs, hence emphasizing the importance of capturing and communicating their living aesthetics. The notion of living aesthetics provides us with a lens to navigate through our design explorations and experiments towards unveiling the potential of Flavobacteria for the design of novel user interfaces.

2.4 Flavobacteria's Structural Color

Flavobacteriia, a taxonomic term for a class of bacteria from the phylum Bacteroidetes, includes many strains of bacteria that can grow as dense, highly organized colonies on surfaces, creating optical structures that interact with light. These bacteria originate from diverse environments and vary in their nutrition dependency and color [38, 48]. In our project, we worked with a wild type strain of Flavobacteria called *Cellulophaga lytica*. This non-pathogenic bacterium originates from marine environments and is known for its stability and brilliant colorations [48]. Flavobacteria's cells, which are 3-4 microns long, move by gliding through which they organize themselves into 2D photonic crystals (2DPC) resulting in structural color [50, 83]. A minimum of 5 to 10 layers of cells is required to form a barely visible response [83], meaning approximately 100 to 1000 cells are required for a minimally detectable structural color. When illuminated, these 2DPCs produce iridescent colors by the interference of scattered light of highly specific wavelengths, at highly specific angles. The periodicity and orientation of the structure of cells is critical in determining the interfering wavelength and thereby the reflected color. In Figure 2, we illustrate the principle behind Flavobacteria's structural color.

Scientists have explored Flavobacteria's ability to self-organize into 2DPCs [33, 38, 48–51, 83] and how environmental factors such as nutrition, salinity and temperature can affect this. Johansen et al. [38] identified certain genes in the Flavobacteria, Flavobacterium strain IR1, that are responsible for the cell organization and the resulting structural color. This cell organization was later linked to the ability of IR1 to consume other bacteria for nutrients by Hamidjaja et al. [33], granting some preliminary insight as to why Flavobacteria behave in this manner. These studies suggest that Flavobacteria's structural color is programmable through both genetics and environmental stimuli. Nevertheless, whilst the biological understanding of Flavobacteria is increasing, much remains unknown about their potential as responsive media for Living Color Interfaces.

In Table 1, we compare Flavobacteria's distinct living aesthetics with three other color-producing living media mobilized in user interfaces mentioned in the previous sections. This comparison was made based on the mechanism by which the organisms produce visible color and the temporal qualities of the living medium as seen in the table.

Flavobacteria are unusual in the way in which they produce color which is influenced by environmental stimuli, the amount and the age of the cells. The result is a wide array of colors, visible at specific angles, produced by a single type of organism. In addition, this color continuously evolves during the lifetime of the organism, the borders of the colony expand and the colors vary across it. Thus, Flavobacteria's living aesthetics show a direct link to the passage of time, making it possible to distinguish between young, old, and dead sections of the colony. This temporal character is ill-understood for Flavobacteria as a living medium and therefore this paper's focal point.

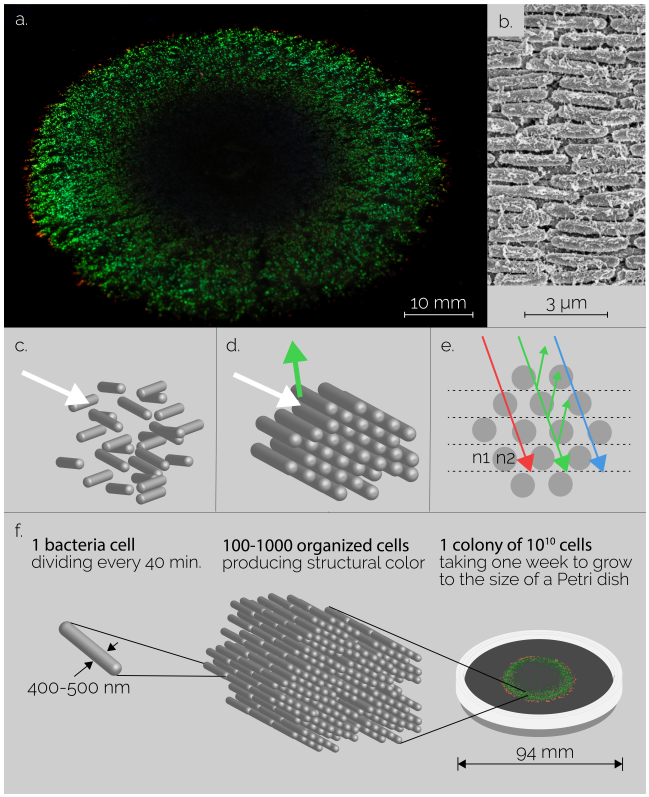


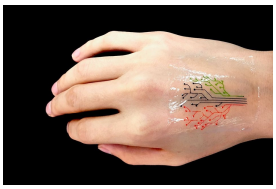
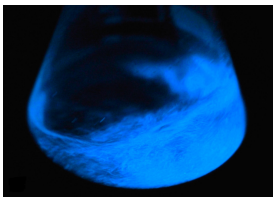
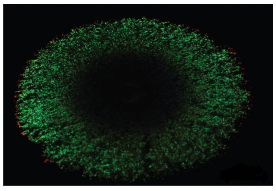
Figure 2: Flavobacteria's structural color. (a) A colony of Flavobacteria with a faded middle. (b) Microscopy of cell organization by courtesy of Hoekmine B.V. (c-d) Light striking, respectively, disordered and ordered bacteria. (e) Light interacting with ordered bacteria cells shown in cross-section with n indicating the different refractive indices of the bacteria cells and the in-between gaps. (f) Zooming out from one bacterium to sufficient cells to display color to an entire colony.

2.5 Capturing and Characterizing Living Iridescent Color

The term 'color' refers to a *perceptual* attribute of a material (in this case, Flavobacteria as a living medium), which is the subsequent effect of the human visual system processing a light-material interaction signal. This means that perceived color cannot be directly linked to physical material parameters or properties of light [63]. More so, understanding iridescent color perception is challenging, as the hue, saturation and brightness of structurally colored materials can vary greatly, depending on viewing geometry [88].

The mechanisms responsible for producing structural color and its function in nature have long been discussed in literature [3, 18, 56, 84, 87, 94]. Existing tools and approaches to capture and characterize appearances, including iridescence, revolve around capturing a sample whilst varying illumination and viewing angle [31, 95]. Alternatively, physical parameters of the sample, such as nanostructure, layer thickness and refractive index can be measured, serving as input to physically based appearance models [95]. The

Table 1: Flavobacteria's living aesthetics compared to other color-producing organisms used in LCIs.

	Organism	Color Producing Mechanism	Temporal Qualities
 [a]	Pigment producing bacteria (Escherichia coli) [86]	3D printed chemical signalling agents incite genetically engineered bacteria, immobilized in hydrogel, to produce various pigments.	The color appears gradually over the course of 24 hours. When the bacteria die, the color remains stable, for how long is, however, unspecified.
	Fluorescent bacteria (Escherichia coli) [61]	Diffusion of chemical signaling agents trigger genetically engineered bacteria, bioprinted in a hydrogel, to produce green fluorescent proteins.	When activated, color appears after 2 hours and is at full brightness after 8 hours. The bacteria live for up to 3 days but how long the color lasts and if the process is repeatable is unspecified.
	Bioluminescent algae (Pyrocystis fusiformis) [5, 71]	Algae grown in a liquid culture produce blue light when stimulated kinetically. This process can be repeated until the algae run out of energy. They then have to recharge through photosynthesis.	The bioluminescent algae have the ability to produce color instantly when stimulated. Depending on the type of kinetic stimuli, the color will last between 30 and 300 seconds.
	Iridescent Flavobacteria (Cellulophaga lytica) [38]	Grown on a surface and influenced by environmental stimuli, bacteria create photonic structures that refract incoming light, resulting in a wide spectrum of color visible at specific angles.	Color emerges 8 hours after the start of growth. The colony increases in size and changes in color distribution over the course of days. After about 7 days, the bacteria die and the color fades.

[a]Vespers. Series III. Designed by Neri Oxman and The Mediated Matter Group for The New Ancient Collection curated and 3D printed by Stratasys. Photo: Yoram Reshef.

challenge of arriving at a universal approach of capturing and characterizing structural color, often with an iridescent appearance, lies in the complexity and variation of (nano-)structures found in nature. These structures lead to remarkable shifts in appearance, depending on viewing geometry, which are often difficult to model or predict. On top of that, appearances are in many cases also influenced by other light scattering effects, which need to be disentangled to enable robust modeling. Given the perceptual and technical complexity, the challenge of capturing and communicating iridescent colors unambiguously has remained to date, as highlighted by, for instance, Seago et al. [84].

The complexity of capturing and characterizing the iridescent colors of Flavobacteria lies not only in the fact that the color appearance varies as a function of the light or view angle. Due to its living nature, its appearance also varies across the surface as a consequence of being at different growth stages at different sections of a colony and consequently, it also changes over time. In previous publications [38, 50, 83], photographs of Flavobacteria have been presented, captured from several angles, to illustrate their iridescent color. These examples, although the photographs illustrate the presence of iridescence, remain insufficient to visualize the striking visual effects of its iridescent qualities, due to a limited set of angle configurations (i.e., changing either the illumination or the view angle). Johansen et al. [38] also present diagrams relating the view angle to spectral power distribution at a fixed illumination angle. The diagrams, providing a very compact representation of the reflected intensity at various angles, are non-intuitive, and thereby difficult to interpret when evaluating living aesthetics. Moreover, neither photographs nor diagrams show the temporal iridescent variations. In short, to our knowledge, no approach exists to capture and characterize iridescent material appearances with temporal and spatial variation at the same time.

3 DESIGN SPACE

3.1 Our Approach

Throughout this project, we adopted an interdisciplinary approach to biodesign, establishing a close collaborative team that includes experts from microbiology, vision and imaging sciences and design. We followed a material-driven design approach [45, 46], which motivates a back-and-forth thinking between the 'details' of this organism, i.e., the biological behavior and characteristics, and the 'wholeness' [98], i.e., the way in which the resulting media is appraised within a composition from a design perspective.

After understanding basic protocols to cultivate Flavobacteria, we followed a hands-on tinkering process, [45, 73] in which we

explored the effects of different environmental factors, and various inoculation techniques on the aesthetic expression of the living medium. Our design explorations, in-depth discussions on our findings within our interdisciplinary team, and the background literature helped us to identify the constraints, opportunities, and potentials (in this case, humidity) to be further explored in a systematic study. In parallel, we identified main qualities that characterize Flavobacteria's living aesthetics.

3.2 Cultivating Flavobacteria

In order to form optical structures, Flavobacteria require a suitable habitat that provides the optimal salinity, nutrients, humidity, access to oxygen and a semi-solid, hydrated surface to interact and grow on. In addition, it has to maintain a sterile environment. This is to protect Flavobacteria from contaminants and potentially invasive external microbial competitors, which can compromise optimal Flavobacterial growth and color expression. Maintaining this sterility during the making process and growth phase is a vital aspect of working with Flavobacteria and any other microorganism, requiring the use of specialized lab equipment such as a laminar flow cabinet.

Flavobacteria's habitat is prepared according to the protocol shown in Figure 3a. It starts with mixing the medium that contains nutrients as well as agar and a black pigment (see Supplement S.1 for the full medium recipe). The agar medium, once solidified, will form a hydrated and nutritious gel surface on which the Flavobacteria can organize into their optical structures. The pigment will provide for a black background, contrasting with the structural colorations so they are clearly visible. After mixing, the medium is sterilized by autoclaving at 121°C and poured under sterile conditions in a Petri dish when it is still hot and liquid. It is then allowed to cool off and solidify. After this, a small amount of bacterial cells are applied with a sterile loop to the surface, called the inoculation (Figure 3b). The Petri dish is then closed and sealed off by parafilm, which allows for air-permeability whilst maintaining sterility and humidity inside the Petri dish. The bacteria then grow at room temperature for a week.

3.3 Growth and Types of Change

When inoculated in the middle of a Petri dish, Flavobacteria will grow outwards at around 5 mm per day and form optical structures as shown in Figure 4. The colony will expand until it reaches the outer edges of the Petri dish. At this point, Flavobacteria will deplete the available nutrients and start to die, causing the iridescent colors to fade away. The total expansion and lifespan of the colony are thus limited by both the size of the Petri dish and the available nutrients. Across the colony, depending on the age, amount and arrangement of bacterial cells, the colorations will vary. Typically, the younger sections, located at the edge of the colony will display red and purple hues, when they mature, the color will change to green, and ultimately, the iridescent colors will fade away, as can be seen in the oldest, middle part of the colony (Figure 4b).

Building upon these initial findings and the existing literature on Flavobacteria, we identified three types of change in the appearance of Flavobacteria, namely form, texture and iridescent color (Figure 4c), resulting from their growth and reproduction. While these

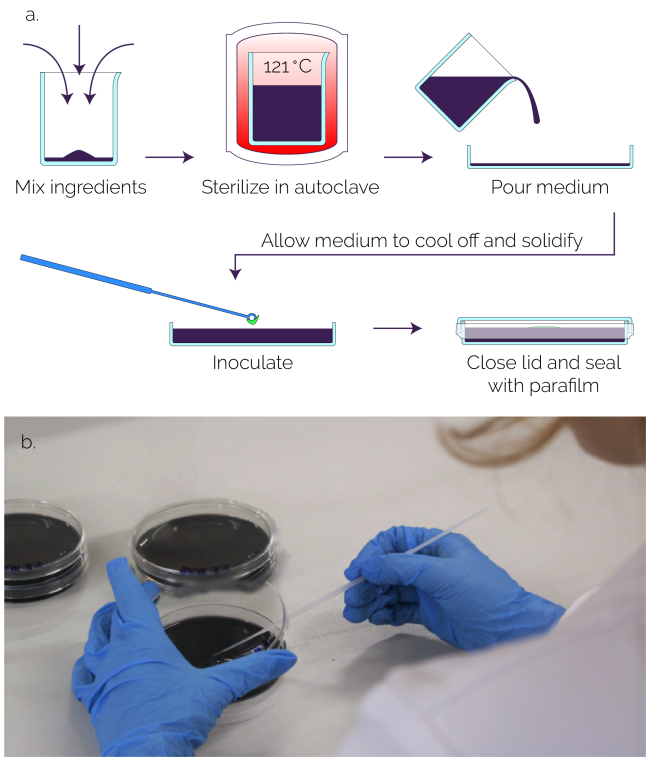


Figure 3: Cultivating Flavobacteria. (a) Infographic on the protocol steps. (b) Inoculating Flavobacteria inside the laminated airflow hood.

highly interrelated changes are not instantly evident when viewing the Flavobacteria, they will reveal themselves over the course of days, resulting in their distinct living aesthetics.

Form. The first type of change refers to the overall form of the colony and how it expands over time, resulting in a specific *shape* and *size* of the colony. For example, Flavobacteria's expansion rate can be evenly distributed, resulting in a *circular* shape or the colony can take an *amorphous* shape, due to some sections expanding out faster than others. The shape of the colony can also be experienced as *hollow* or *full*, which is determined by the distribution of the iridescent sections of the colony. The overall perceived texture of the living medium plays a very important role in this.

Texture. The second type of change refers to the texture of living medium, which is mostly determined by the distribution of iridescent sections on the surface area. Flavobacteria can form a *scattered* and *pointillistic* color distribution, which is experienced as a *rough* texture; or a *dense* and *uniform* color distribution which results in a *smooth* texture.

Iridescent Color. The third type of change refers to the iridescent color of the colony and can be described through the qualities of *hue variation* and *brilliance*, which are dependent on the viewing angle. A colony of Flavobacteria can appear *mono colored* or *multicolored*, as well as *bright* or *dull*.

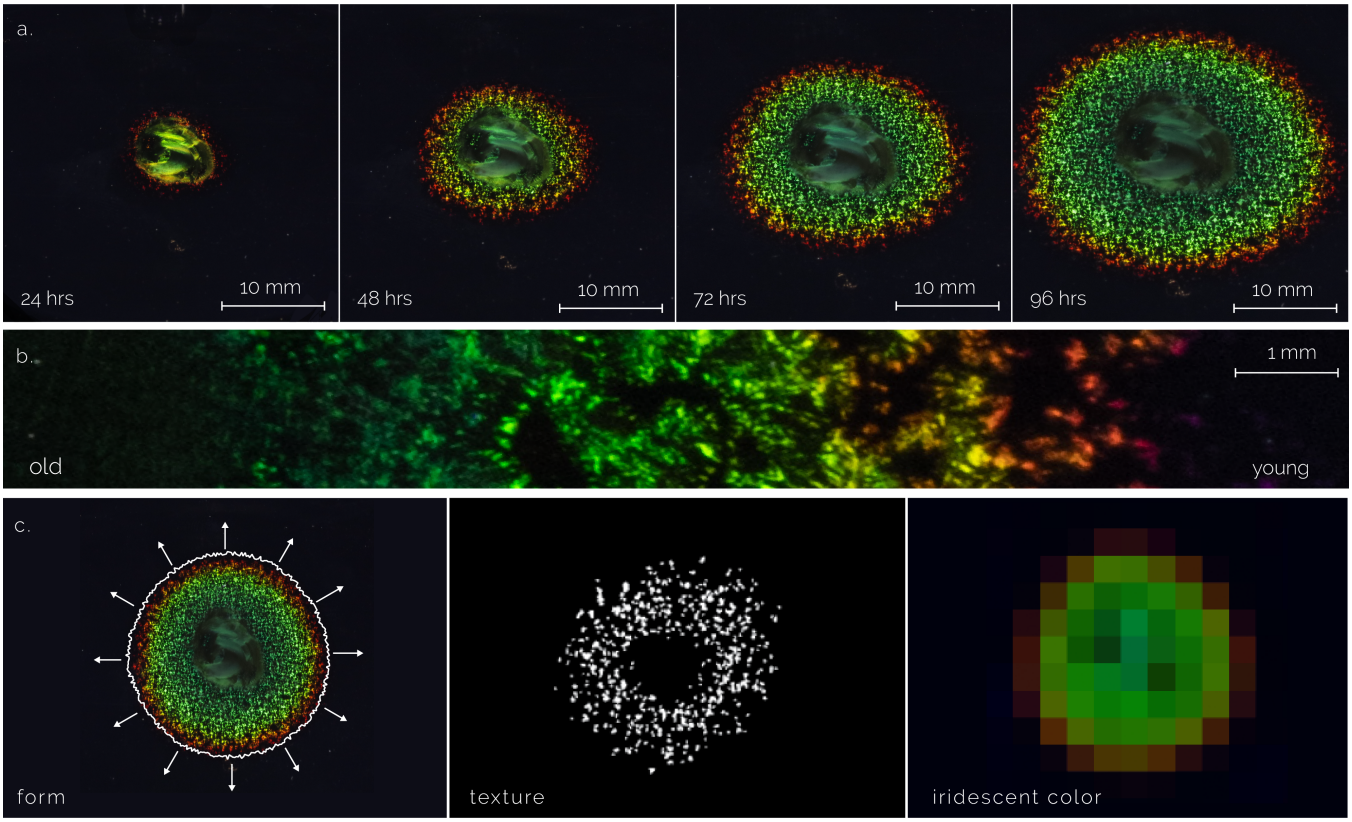


Figure 4: Growth and types of change. (a) Growth of Flavobacteria over 96 hours, captured and illuminated from 45°. (b) Close-up of the colony from its center to the edge. (c) Types of change deduced from the growth.

3.4 Initial Design Explorations

Having established a method of cultivating Flavobacteria whilst identifying the types of change in their living aesthetics, we started tinkering with the organism. We observed their temporal behavior under different circumstances and with variations in the basic protocol. This exploration resulted in diverse expressions of form, texture and iridescent color of the living medium which are displayed in Figure 5.

Environmental stimuli affect the living aesthetics of Flavobacteria (Figure 5a). Here, influencing their growth through introducing a low temperature, high humidity or a deficiency in nutrients, will cause their form, texture and iridescent color to vary noticeably.

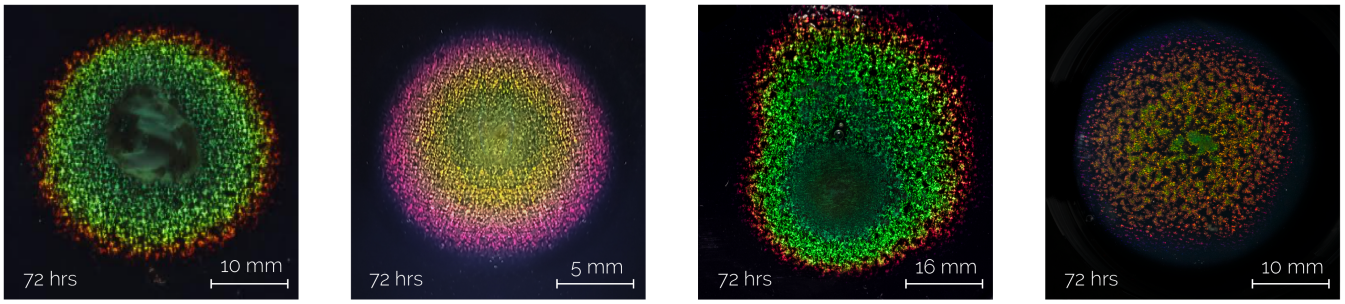
Flavobacteria interact with other microbial species such as bacteria or fungi, resulting in unexpected colorations (Figure 5b). When different species of Flavobacteria encounter, they tend not to combine and instead expand in the opposite direction. The presence of fungi often seemed to inhibit the brilliance of Flavobacteria's color where the presence of other types of bacteria did not. In another instance, Flavobacteria seemed to coexist with other species of bacteria, resulting in a larger expansion rate and unique texture across the colony.

It is possible to change Flavobacteria's living color through different inoculation methods or by modifying the colonies during their growth (Figure 5c). Inoculation, by means of a loop or by dripping liquid culture containing bacterial cells, will determine the starting point of the colony's growth. In a more direct manner, the colonies can also be modified during growth, altering its form expansion, texture and color qualities. In a similar manner, it is possible to tune their living color by varying the shape, size, flexibility and surface texture of the habitat (Figure 5d). Here, Flavobacteria will arrange themselves onto any given type of surface. For example, they will grow and align themselves along fine textures faster than across flat surfaces, causing alternate forms, textures and colors to appear.

When given a larger scale habitat, Flavobacteria also have the potential to grow for longer periods of time. Yet, after a period of one or two weeks, such large-scale habitats were found to dehydrate up to a point where Flavobacteria's expansion and color were very much diminished (see Figure 5d, large scale habitat). This highlights a wider microbiological issue, methods are limited to the use of the Petri dish, which does not enable long term or automated cultivation of bacteria. Through these explorations, we established an initial understanding of the organism's behavior and how it is influenced by diverse input mechanisms.

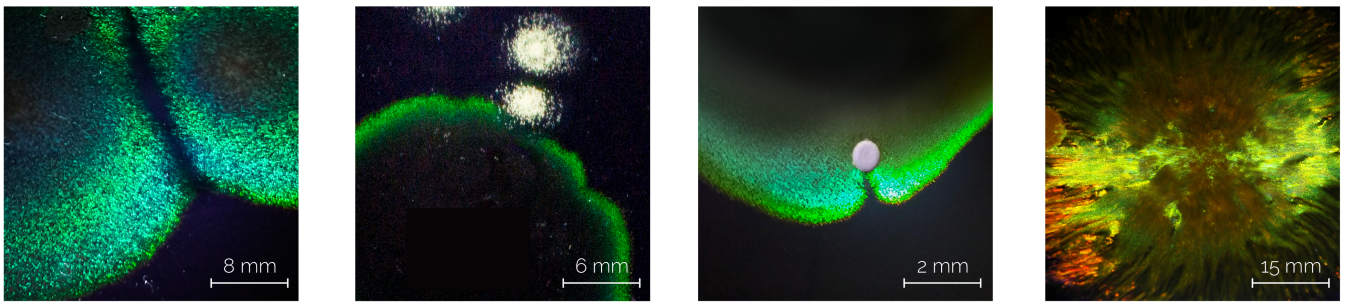
In the next section, we describe the investigation of one of these input mechanisms, i.e., humidity, for the following reasons: Firstly, when attempting to grow Flavobacteria over a longer period, the role of humidity is deemed crucial in enabling their long-term vitality. However, there is a gap in microbiological literature when

a. environmental stimuli



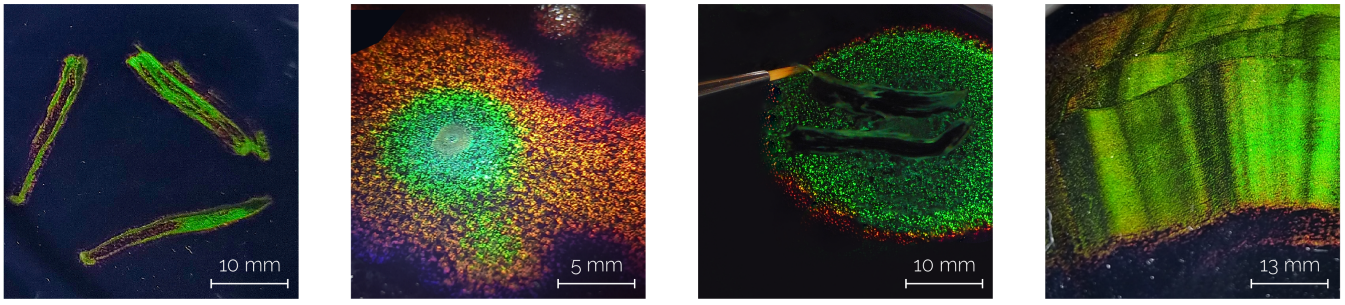
standard conditions (t=21 C, RH=70%, NUTR=100%) | low temperature t = 8℃ | high humidity RH = 95~% | low nutrients NUTR = 50%

b. interactions with other organisms



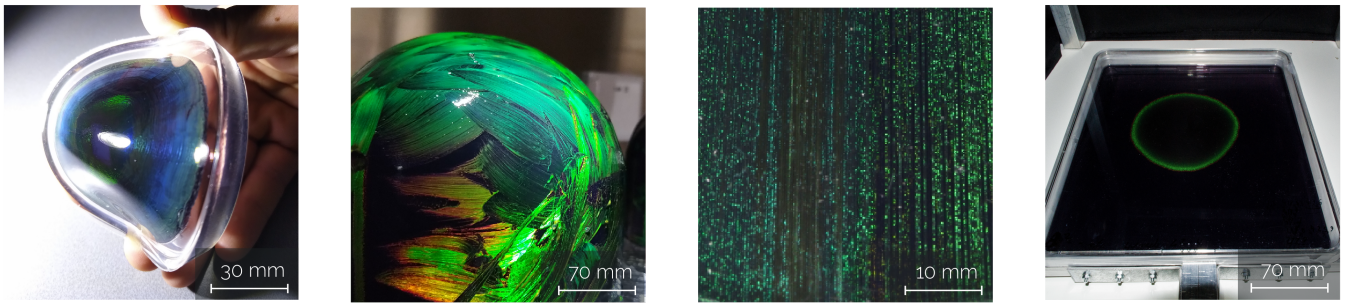
other Flavobacteria | fungi | other bacteria | other bacteria (coexistence)

c. direct human input



spread with an inoculation loop | dripping liquid culture | disrupted with a brush | spread with a spatula

d. habitat shape and dimensions



flexible habitat | 3D shaped habitat | textured surface | large scale habitat

Figure 5: Initial design explorations with Flavobacteria.

it comes to the role of humidity on the organism's vitality. Secondly, humidity influences the way in which Flavobacteria propagate, i.e., their *gliding motility* [33]. As a result, the humidity levels present in their habitat were found to be especially influential in their expansion rate, resulting in the most striking effects on the colony's ultimate form (besides color and texture). We foresee humidity as a potential input mechanism in LCIs, for example, for more expressively embodying diverse data in bio-digital hybrid systems.

4 A STUDY ON FLAVOBACTERIA'S LIVING AESTHETICS

In this section, we present a controlled study in which we investigate Flavobacteria's living aesthetics in relation to humidity as an input mechanism resulting in drastic changes in Flavobacteria's living aesthetics. The temporal and iridescent aspects of this living medium require a setup to enable a relatively fast and automated acquisition in which a sample of Flavobacteria is captured and illuminated from different angles. Hence, we first designed a capture tool.

4.1 Development of the Capture Tool

Similar to existing tools developed to capture material appearances [31], our capture tool should hold a sample while varying illumination and view angle to capture its iridescent colors. Therefore, our capture tool contains a sample holder, which can tilt and rotate a Petri dish. The Canon EOS 5ds camera is placed on a tripod at a fixed position. Since we are primarily interested in their appearance to the human eye, it suffices to capture its appearance via such a RGB system.

Light scattering measurements of the Flavobacterial strain IR1 performed by Schertel et al. [83] suggest an intense structural reflectance peak when placing the camera and light at the same spot (i.e., retroreflection). This was also perceived during our initial observations. Therefore, our tool contains an LED ring through which the camera can capture retroreflection in a simple, practical manner. The LED ring is mounted on a rotating arm in order to move around the sample. This allows for varying the illumination angle in relation to the view angle. Alternatively, a ring flash can be used to illuminate the sample supposing only the retroreflection of the sample must be captured (see Figure 6).

To enable an efficient acquisition of the temporal changes of Flavobacteria, we automated the activation of the light, camera shooting, and the movement of the Petri dish and the LED ring through an Arduino microcontroller. We placed the components of the capture tool in an MDF box and painted the inside of the box in black to eliminate light from the environment (Figure 6b,c).

4.1.1 Determining the Suitable Configurations for this Study. While capturing images of Flavobacteria with the capture tool from different angle configurations, it became clear that, from all the possible configurations, placing the camera and light at the same spot resulted in the most vivid structural color. Hence, for this study, instead of the LED ring on the rotating arm, the ring flash was used. The incident angle α (Figure 7a) was varied in order to take Flavobacteria's angle-dependency into account, resulting in four different angle configurations. We set the minimum and maximum of this incident angle to 30° and 75° to generate relevant data despite

Figure 6: The capture tool. (a) Infographic of the capture tool. (b-c) The protective MDF box from the outside and inside.

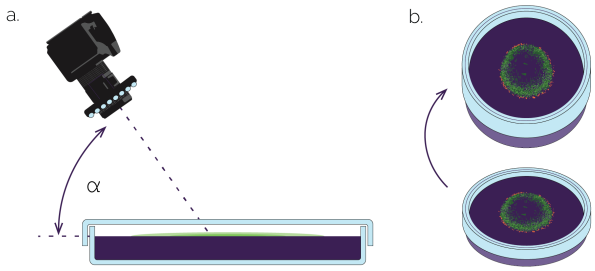


Figure 7: Data processing. (a) Capturing a sample with incident angle α (= angle between sample surface and the direction of camera and ring flash). (b) The perspective transformation of captured data.

the perspective and spectral reflection in the lid of the Petri dish. Accordingly, in our study, we decided to place the camera and light at the same spot while capturing from incident angles of 30°, 45°, 60° and 75°.

4.1.2 Data Processing. To easily compare captured data, images were transformed to correct the perspective, corresponding to the incident angle (Figure 7b). Additionally, a Python script was created to digitally analyze the data and perform objective measurements. Based on brightness-thresholding, quantitative values were automatically extracted for the surface area of the colony, as well as for the ratio of structural colored areas in relation to the entire colony. These values support the analysis of the overall form of the colonies.

4.2 Living Aesthetics of Flavobacteria in Response to Humidity

4.2.1 Procedure. During the study, Flavobacteria were grown at three different levels of humidity: low, medium and high. This was done by keeping the initial humidity present in the Petri dishes constant by fixing the amount of growth medium, pouring temperature and evaporation time. Regulation of humidity was then established by placing the Petri dishes, loosely closed, inside an incubator with varying relative humidity levels as low (35%), medium (65%) and high (95%). The samples were captured with the capture tool from the four angle configurations on the 3rd, 5th and 7th day. Based on the data, including about 360 images, the relation was explored between humidity and living aesthetics, characterized by form, texture and iridescent color. For every humidity level, one representative sample was identified that showed the most common living aesthetics within that group. These samples are used throughout the next section to visualize the results.

The relation between humidity and the colony's **form** was explored based on the data captured from 60°. This angle maximizes the intensity of structural color but minimizes loss of information due to perspective. To study the size of the colonies, a value was extracted through the digital analysis for the surface area. This value was translated into the average expansion rate for all three different levels of humidity. The shape of the colonies was analyzed by comparing perspective-corrected images. Additionally, a value was extracted through digital analysis for the ratio between structural colored areas and the entire colony in order to determine the fullness of the shape. To explore the relation between humidity and the **texture**, we again used the data captured from 60°. Binary images were created through brightness-thresholding for the three representative samples. Here, colored sections of the colony are represented by white pixels, clearly visualizing the distribution of iridescent sections. In order to explore the relation between humidity and the **iridescent color**, the representative samples were cropped and ordered in an overview by incident angle, humidity level and day. From here, the change over time in hue variations and brilliance of the colonies could be compared between different incident angles and humidity levels.

4.2.2 Results. A higher humidity results in an increase in the colonies' size, i.e., a higher expansion rate. Because the samples in the most humid environment reached the edge of the Petri dish by day 5, the expansion rate was extracted from the data until day 5. Figure 8 shows these expansion rates for the different levels of humidity together with the representative samples and their outline on day 3. As can be seen in the overview, firstly, the colonies in a humid environment form a more amorphous shape, whereas the colonies in low humidity tend to form a refined circular shape. Secondly, the low humidity samples appear more hollow on day 5 than the high humidity samples. This was validated by the automatically extracted ratios between the structural colored area and the entire colonies (see the digital analysis results in Supplement S.2). Due to this relatively low ratio and the dense distribution of the colored sections (see also Figure 9), the low humidity sample forms a refined colored ring with a thin wall-thickness.

The structural color formed in high humidity appears scattered and pointillistic which gives a rough expression in terms of texture

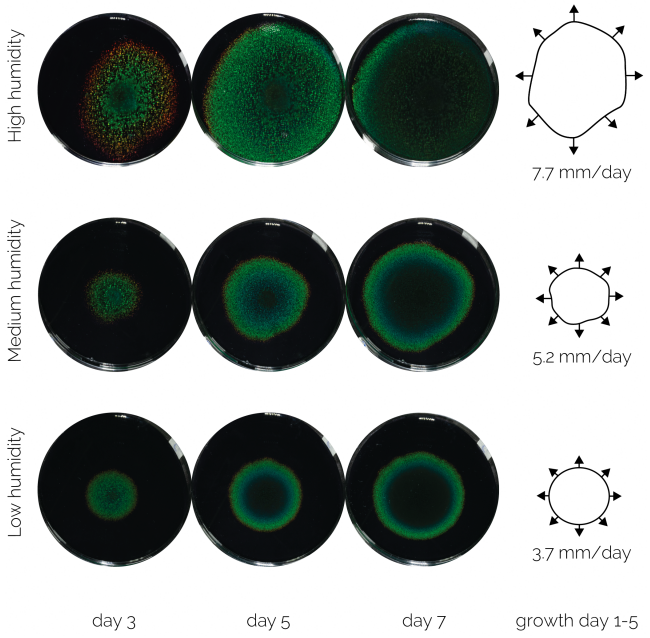


Figure 8: Representative samples and their outline illustrating the form-humidity relation.

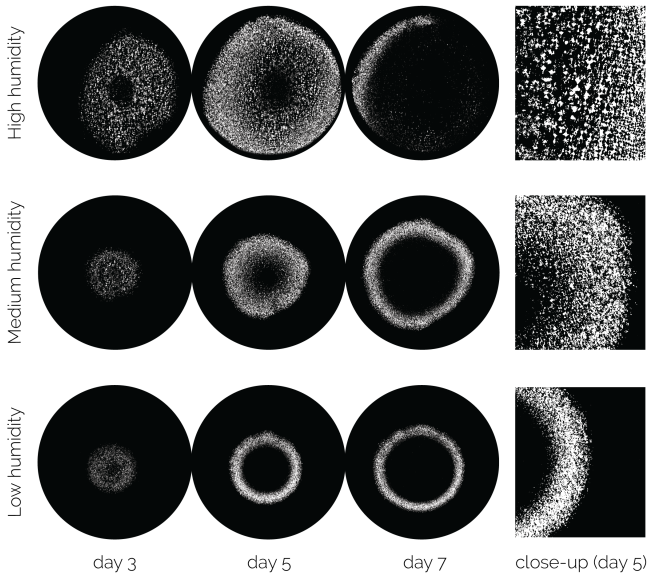


Figure 9: Binary images of representative samples illustrating the texture-humidity relations.

(Figure 9). Correspondingly, low humidity results in a dense and uniform distribution of color, which gives a smooth texture.

The iridescent color of the representative samples can be seen in Figure 10. For all the different levels of humidity, Flavobacteria

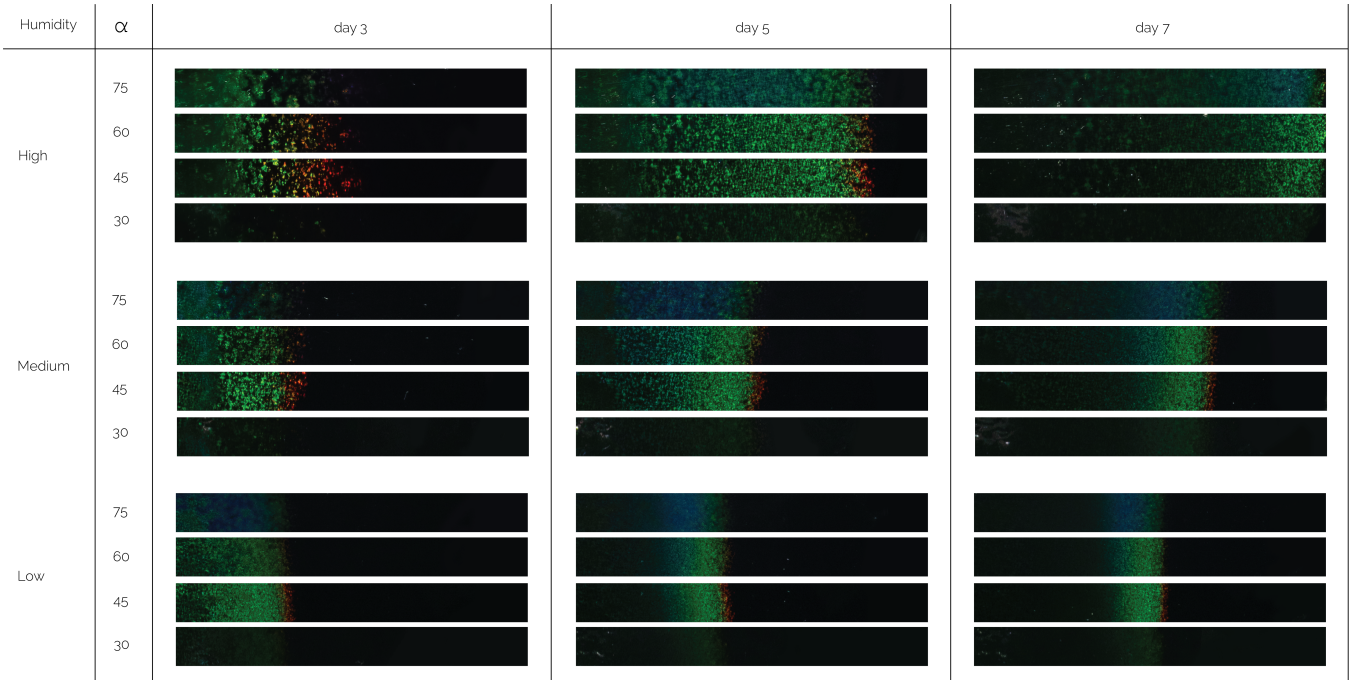


Figure 10: The representative samples, cropped from the middle of the colony to the edge of the Petri dish, illustrating the iridescent color-humidity relations.

appear the most brilliant and multicolored from a viewing angle between 45° and 60°. The variations in hue seem to decrease over time (e.g., high humidity, day 3 sample vs. high humidity, day 5 sample) as well as in conjunction with the humidity (e.g., high humidity, day 3 sample vs. low humidity, day 3 sample). The brilliance of the iridescent color appears slightly more intense at a higher humidity but does not seem to be affected by time (e.g., low humidity sample on day 3 vs. low humidity sample on day 7).

4.2.3 Key Takeaways. Flavobacteria's living aesthetics are affected by the humidity in multiple ways: a higher humidity results in a higher expansion rate, more amorphous shapes and more scattered and pointillistic colored sections of a colony. The iridescent color of the colonies appears slightly more brilliant and multi-colored at high humidity. This study grants initial insights on how Flavobacteria's living aesthetics develop over time. However, samples grown at a high humidity reached the limits of their habitat in a matter of 5 days, making it impossible to study this behavior over longer periods of time. In addition, capturing was done at a low frequency (i.e., every 2 days), leaving gaps of information on how Flavobacteria's living aesthetics were developing in-between. To overcome these drawbacks in exploring the potential of Flavobacteria for LCIs, we developed Flavorium, which we present in the next section.

5 FLAVORIUM

Flavorium is a large-scale habitat that allows for the long-term growth of Flavobacteria and automatic capturing of their growth. It grants control over the humidity present inside the habitat since dehydration was found to be the main inhibitor during the initial exploration towards up-scaling (Section 3.3). Flavorium also optimizes other conditions such as nutrients, sterility and access to oxygen, enabling us to study Flavobacteria's living aesthetics across new spatial and temporal scales.

5.1 Design and Prototyping

The development of Flavorium required multiple iterations. Here, a challenge was maintaining the sterility during assembly and growth whilst keeping the habitat air-permeable to supply Flavobacteria with oxygen. This permeability was also needed to allow humidified air to both enter and escape the habitat, allowing control over the humidity levels, which contrasts with the need to keep the habitat sterile.

In the final version (Figure 11), this was resolved by introducing a separation between the sterile inner area and non-sterile outer area in Flavorium. The inner area is connected to the outer area using barriers that allow air to pass through whilst keeping contaminants out. The outer area was therefore not required to be sterile and consequently used to regulate the humidity. This was done with a digitally controlled ultrasonic transducer producing mist and fan that effectively blows the mist into the outer habitat. The resulting humidity levels are monitored by four sensors which transfer this information to the Arduino microcontroller that, via a closed loop system, orders the ultrasonic transducer and fan to turn on or off. The measured humidity values are also documented by a laptop. The Arduino also triggers the Canon EOS 250d camera, equipped with a ring flash and set at a 45° angle from the colony, to take a picture at a given moment. To easily divide mist inside the habitat, we adopted a vertical orientation of the colony.

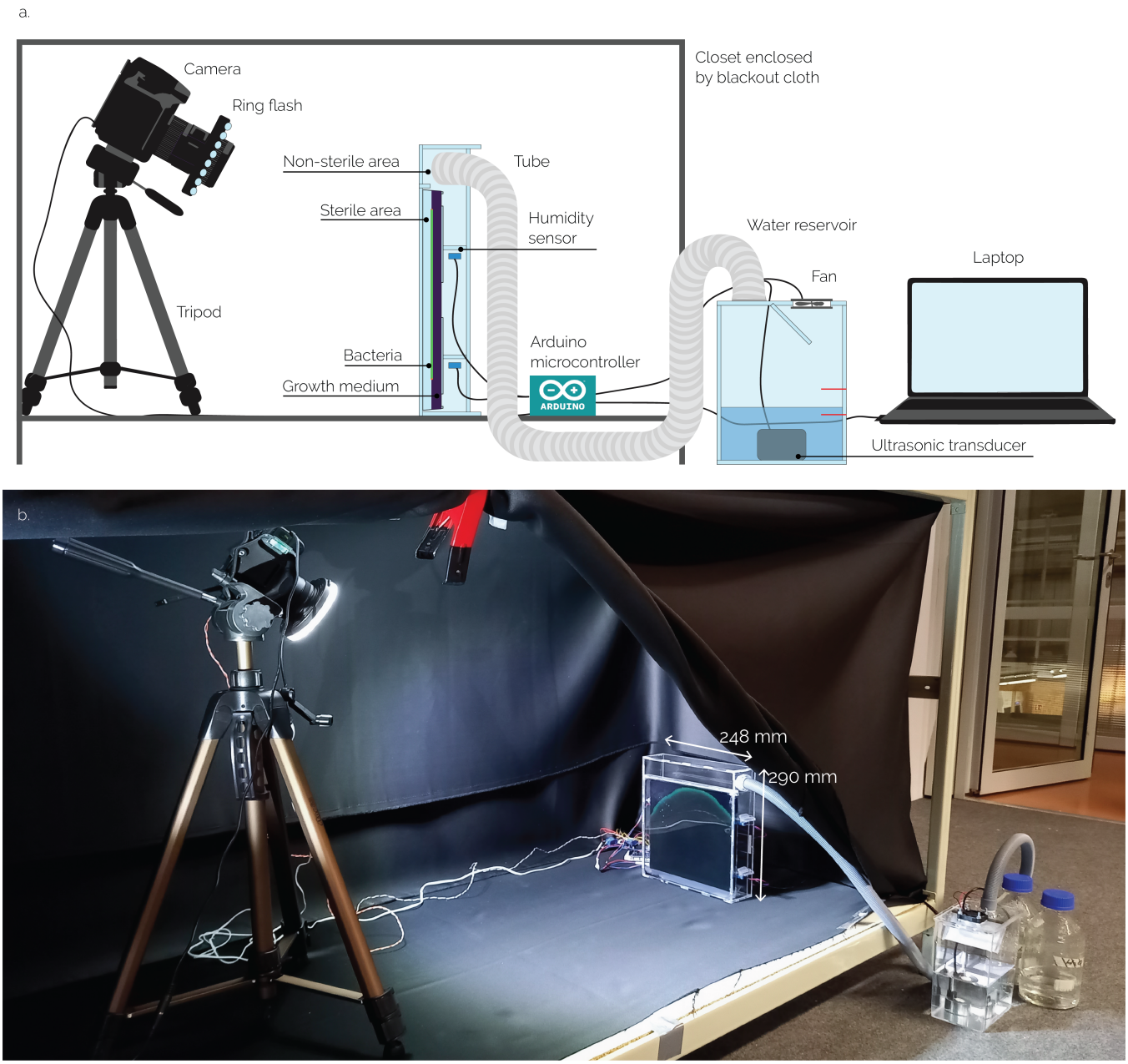


Figure 11: The Flavorium habitat. (a) Infographic of Flavorium. (b) Image of actual setup.

5.2 Initial Observations

As an initial test, we ran the Flavorium for a full month at a high relative humidity. This builds on the controlled study (Section 4.2) where the samples grown at a high humidity were restricted by the size of their Petri dish after five days. To get a better understanding of how this behavior in humid conditions develops, the Flavorium was thus set at a relative humidity of 90%. This resulted in a large colony of Flavobacteria that was captured at hourly intervals, providing unique footage of how the striking living color of Flavobacteria developed over longer periods of time (Figure 12, see also the video footage in Supplement S.3).

As the form of the colony developed over time, spatial variations in expansion rate were observed, with the bottom part expanding faster than the top. Also, the expansion rate appeared to accelerate and decelerate at different points in time, an observation that is made possible by the frequent capturing rate. As the weeks progressed, an increasingly larger part of the colony grew old, losing its iridescent properties and making the colony appear more hollow.

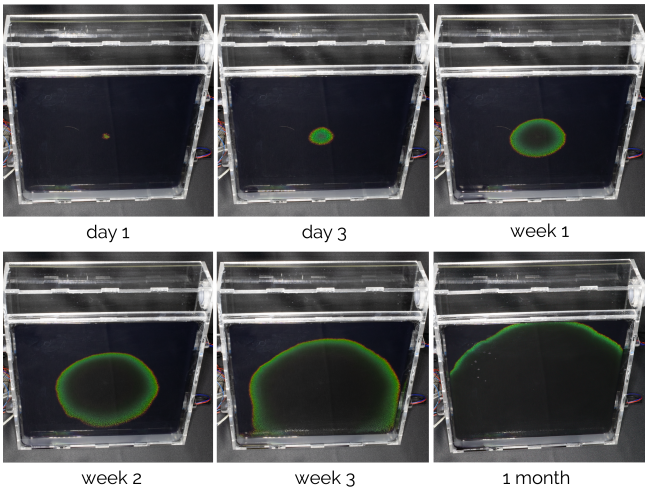


Figure 12: Growth of Flavobacteria up to one month.

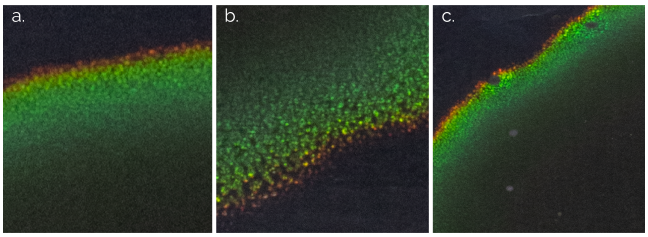


Figure 13: Initial observations with Flavorium. (a) Top part of the colony at 2 weeks. (b) Bottom part of the colony at 2 weeks. (c) Interaction with other bacteria in the 4th week.

Despite this, the younger, outer sections of the colony did retain their iridescent properties, showing a smooth texture at the top of the colony and a pointillistic texture at the bottom sections (Figure 13a and b respectively). This is an unexpected result which we could only obtain thanks to the scale of Flavorium.

Around day 23, an interesting interaction between the Flavobacteria and an invading species of bacteria was observed (Figure 13c). Due to the frequent capturing method, it was possible to observe Flavobacteria performing encircling motions around the other bacteria as described by Hamidjaja et al. [33].

Our initial observations show that the enlarged spatial and temporal scale of Flavorium, as well as the frequent capturing, allowed for unveiling novel potentials of Flavobacteria and its long-term responsive behavior. In the next section, we present possible applications of Flavorium and envision the use of other Flavobacteria-based LCIs in everyday artifacts.

6 APPLICATIONS

We present three application directions for Flavobacteria-based LCIs. The first direction builds upon our bio-digital artifact Flavorium. The other two are informed by our controlled study and design explorations (Section 3 and 4). In the ideation process, we were inspired by the existing body of work in biological HCI, in particular two application domains proposed by Pataranutaporn et al. [77], namely, *embody* and *communicate*, and the notion of *material traces* in HCI to manifest time, skill, and use [25, 82].

6.1 Flavobacteria-based LCIs to Embody Digital Data

The living aesthetics of Flavobacteria can embody digital data in an expressive yet ambient manner. Figure 14 presents a design concept, ***living monitor***, that reflects users' habitual practices through its living aesthetics. The amount of steps per day measured by a smartwatch is translated to the humidity level inside Flavorium. This causes the colony's form, texture, and color to change dynamically, reflecting a person's lifestyle. Depending on the amount of physical activity measured by the smartwatch, the living monitor will either show a rapidly expanding, brightly colored colony or one that is slowly growing and dull. The living aesthetics appeal to *a sense of shared vitality* between the user and the living medium [65], potentially motivating people to change their practices towards more sustainable and healthier directions through relatedness and empathy with living media. Similarly, such LCIs can visualize energy usage at home, data about social interactions or ecology. This could also entail more long-term applications, for example, visualizing energy usage throughout the year given a large-scale habitat that supports continuous growth.

Figure 14: A living monitor embodying the amount of physical activity measured by a smartwatch of a person with an (a) inactive and (b) active lifestyle.

Figure 15: A living label indicating wellbeing of a houseplant.

Figure 16: Living notes enabling playful back-and-forth communication.

6.2 Flavobacteria-based LCIs to Communicate Signals from the Environment

Flavobacteria have proven sensitive to changes in environmental factors like humidity (Section 4) but also changes in temperature and the presence of other microbes (see Figure 4, Section 3). This highlights the potential of these organisms to communicate such changes to us by altering their form, texture and color, providing a living alternative for digital sensors. Such living sensors will have a relatively slow response but offer new interaction possibilities and expressions compared to digital ones. We present such a possibility with the concept of a ***living label***. Given Flavobacteria's sensitivity to humidity, a living label can communicate and amplify the wellbeing or struggle of a houseplant to the caretaker by reacting to the humidity of the soil (Figure 15). Here, Flavobacteria's living aesthetics will synergize with the wellbeing of the plant, allowing humans to participate in this symbiosis by providing care for both. Living labels can also communicate other factors such as fluctuations in temperature over time, for example, relevant for the preservation of food. We envision Flavobacteria-based LCIs that can be attached to everyday artifacts, coupling environmental data to the lifetime of an artifact.

6.3 Flavobacteria-based LCIs to Trace Skill and Use

The peculiar ways in which humans interact with objects and spaces can be captured through Flavobacteria's distinct living aesthetics that enable a patina of ***living traces*** to grow on things of daily use [25, 82]. A playful take on this is our concept of ***living notes***. Flavobacteria can be used to leave notes that are invisible at the time the note is created but only occur over time, with specific stimuli. Based on the current possibilities of Flavobacteria, we developed a simple interaction scenario where users apply a small amount of bacteria on a substrate, barely visible to the eye (Figure 16). In a matter of hours, the message will appear with the growth and reproduction of bacteria. The borders of the colony will expand in the following days, causing the original message to fade. Back and forth communication can be achieved through disrupting the living color with a brush. The temporal aspects of these living notes offer possibilities for playful interactions, opening up a new design space where techniques to interact with such media should be further explored. We discuss some of these future research directions, as well as the limitations of our work in the next section.

7 DISCUSSION

This paper provides an understanding of the living aesthetics of Flavobacteria with the aim of introducing them as a novel living medium for future LCIs. We showed that the structural colorations produced by Flavobacteria are subjected to the organism's growth, reproduction and death, resulting in distinct temporal expressions, i.e., their living aesthetics [44]. We introduced form, texture and iridescent color as the three main changes humans can experience in this living medium. Taking these three elements as a departure point, we discussed how a Flavobacteria-based LCI can be purposefully designed to be experienced as, for example, *circular* or *amorphous*, *hollow* or *full*, *smooth* or *rough*, *mono* or *multi-colored*,

brilliant or *dull*. We also showed how the size of the living media changes over time, and how this change can be *slower* or *faster*. Our bio-digital artifact, Flavorium, with its enlarged spatial and temporal scale, allows for the unveiling of Flavobacteria's novel potentials and their long-term responsive behavior. Building on Flavorium and initial design explorations, we introduced potential application directions for HCI. Here, we discuss the implications and limitations of our work and challenges for HCI designers.

7.1 Opportunities for HCI

Flavobacteria-based LCIs can enrich human sensory experience by embodying digital information [37] as well as communicating signals across scales and environments to create observable output [77]. The delay between input and output, speed of growth and eventual disappearance of color (i.e., the ephemerality of the medium [21]) also point out Flavobacteria's potential for playful interactions in everyday artifacts. By tapping into their potential for tracing skill, use and time in HCI [25, 82], such interactions would extend design possibilities beyond biotic games, where humans interact as active players with biological materials in a game setting [77].

Interfaces that integrate living media appeal to *a sense of shared vitality* [65], promoting empathy with users [32], as discussed in our living monitor concept. Karana et al. [44] explain this reciprocal and evolving relationship between humans and living artifacts with the notion of *mutualistic care*, where humans act upon a living artifact or are encouraged to perform a specific activity (e.g., workout) for it to thrive. Designers of such systems should further explore these evolving relationships between humans and living artifacts for meaningful applications that are more easily assimilated in everyday life. To that end, our paper provides an initial understanding of the experience that a living medium elicits at a sensorial level to express its wellbeing. Opportunities for HCI will arise when other aspects of experience at the *interpretive, affective* and *performative* levels [24] are explored in future studies. This will support a comprehensive understanding of how humans experience living media, for example, as *peaceful, turbulent* [79], *alive* [16, 43], or the extent a living media elicits the feeling of *empathy* [14, 65].

Flavobacteria's temporal and optical properties differ from other living media used in interaction design such as pigment producing bacteria [86], fluorescent bacteria [61] and bioluminescent algae [5, 71]. When inoculated, Flavobacteria show the first signs of structural coloration within hours and grow continuously by expanding the size of their colonies. This growth can be affected in diverse ways, offering a broad design space for HCI researchers as discussed in Section 3. We tap into some of these design potentials, but we are aware that we have only scratched the surface of what novel interactions Flavobacteria could offer for HCI. For example, the angle dependence of Flavobacteria's color offers opportunities for user interfaces where information over time can only be viewed from a certain position. In addition, HCI researchers can explore possibilities for users to activate Flavobacteria's growth or preserve their color by preventing the optical structures from degrading after the death of the organism. We are aware that these directions are first and foremost a novel scientific attempt that requires an interdisciplinary approach. Yet when achieved, they will open up possibilities for novel user interfaces. Another opportunity for HCI designers is the possibility of designing both *open* and *closed* living interfaces [71] with Flavobacteria. As in the Living Notes concept, an open system allows for direct interactions with Flavobacteria during growth, before or after the appearance of the living color. When disrupted by such interactions, Flavobacteria will reorganize their colonies resulting in surprising colorations. This aspect is very peculiar to Flavobacteria, which we have not seen explored with other living media in HCI. Thus, although direct interactions with Flavobacteria in an open system contrast with the need to maintain sterility, it results in unexpected emergent behavior that can be used as a design strategy to express the livingness of a media.

Discovering and mobilizing this emergent behavior of complex biological systems, referred to as life's useful properties by philosopher Marc Bedau [6], is a challenging yet exciting future research direction for HCI. Herein, we foresee possibilities for AI supported symbiotic systems, where algorithms learn from emergent behavior of living media while helping the system optimize. Such bio-digital hybrid systems will play a critical role in real-life longitudinal studies, where designers can explore the way the human body and other living and non-living entities condition the livingness of the media, i.e., *habitabilities* [44].

7.2 Design Challenges

Although our work shows that using Flavobacteria as a medium for future LCIs is possible, several practical limitations still exist for HCI designers. Flavobacteria require a suitable habitat with optimal conditions to thrive and produce structural color. One of the practical challenges here concerns maintaining these conditions which is not straightforward for HCI designers with no microbiology background. It requires understanding the bioprocess to sustain certain nutrients and by-products in a habitat. This calls for new interdisciplinary alliances and urges HCI designers to broaden their investigations to systems for long term use and maintenance of bio-digital hybrids. Designers should consider to what extent such a system needs maintenance by humans or whether it can be a self-sustaining habitat [44] that adapts and evolves with digital and microbial intelligence in synergy.

Flavobacteria-based LCIs should provide a sterile environment that protects Flavobacteria from contaminants which will affect their growth and structural colorations. Therefore, specialized biolab equipment is necessary for working with Flavobacteria. Using a standard Petri dish inside a laminar flow cabinet is a quick way to start initial design explorations whilst maintaining sterility. However, the use of a standard Petri dish can limit the growth of Flavobacteria to a maximum of 5-7 days and poses challenges in maintaining the stable conditions necessary for controlled studies. To address this and enable further studies into Flavobacteria's living aesthetics, we developed Flavorium. We envision that the design of custom-made habitats as research artifacts, therefore, will be a common first step in any biodesign process, facilitating research into the behavior of a living medium over a longer period of time. Providing optimal growing conditions whilst maintaining sterility required multiple iterations in developing Flavorium. We hope our design process will guide other HCI designers in the development of such habitats.

7.3 Limitations and Future Work

The visual data from our characterization study shows distinct changes in how the living medium's form, texture and iridescent color develop over time for different humidity levels. Yet, the humidity was kept constant for each colony, thus granting no insight on how a single colony of Flavobacteria responds to variations in humidity over time. We aim to explore this in the future with Flavorium. Furthermore, although we explored many input mechanisms in our design explorations (Section 3), our controlled study (Section 4) focused on a single factor, i.e., humidity. In future studies, we aim to explore relationships between Flavobacteria's living aesthetics and different environmental factors such as temperature, air quality and the presence of other microbes, which will open up new avenues for designing LCIs.

In this paper, we focused on capturing and characterizing Flavobacteria's living aesthetics by bridging the fields of biology, vision and imaging sciences, and design. We developed a tool that allows for comparing colonies' living aesthetics by systematically capturing them. Some aspects of our capture tool can be further developed, such as the implementation of a more precise directional light source with an evenly distributed spectrum. Additionally, color calibration could be considered. While analyzing the captured data, we manually defined the brightness threshold through an iterative process by comparing an actual sample with visual outcomes of the digital analysis. Although our analysis for all samples relied on the same threshold value, in future studies, this value can be defined through digital tools for more accurate results. Our tool can be used in future research for modeling and simulating Flavobacteria's living aesthetics. Such research will support designers in understanding the microorganism's structural color by not necessarily going through all the lab experiments themselves. Scholars in computer graphics have proposed approaches focusing on rendering spatially varying appearance [23, 66] or time-varying appearance [9, 11, 30, 89]. Approaches, although limited, also exist for rendering iridescent colors [7]. Nonetheless, researchers point out that fitting such models to measured data of real-world iridescent surfaces remains future work.

Our approach, grounded in material-driven design [45], has been collaborative in nature, letting the organism express itself and interpreting how this expression can be experienced. Here, we favored the organism's own agency over the ability to control its behavior and therefore, preferred a wild-type organism (i.e., not genetically modified). However, recent developments at the crossovers of synthetic biology and materials science enable the development of *Engineered Living Materials* [26, 69], which profoundly rely on the genetic modification of organisms in biodesign. Flavobacteria's behavior can be genetically programmed [38], offering the potential to, for example, change their sensitivity to certain stimuli, the colors they produce, or the way their colonies form. This puts forward the ethical significance and debate surrounding synthetic biology [19, 40, 44, 71] and invites us to think about future HCI studies on potential ethical concerns that such living media might elicit.

8 CONCLUSION

Through their dynamic and vivid iridescent colorations, clearly visible by the naked eye, Flavobacteria show potential as a medium for future user interfaces. In this paper, we explored Flavobacteria's potential by zooming in on their behavior and the way in which their expression changes over time, i.e., their living aesthetics. Because Flavobacteria's appearance is highly complex, being both angle-dependent and temporal, we first created a tool to capture and characterize their living aesthetics. Secondly, to enable long term observation, we designed Flavorium, a habitat that allows for large scale growth of microorganisms and a means of documentation. Flavorium also allows designers to tune growing conditions in a more controlled manner, bringing forth the responsive behavior of Flavobacteria and their applicability in future Living Color Interfaces. We present some potential directions with Flavobacteria-based LCIs for embodying digital and environmental data, for playful interactions with living media and material traces.

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