(Re)activate, (Re)direct, (Re)arrange: Exploring the Design Space of Direct Interactions with Flavobacteria

Clarice Risseeuw
c.c.risseeuw@tudelft.nl
Delft University of Technology
Delft, The Netherlands

Holly McQuillan
h.l.mcquillan@tudelft.nl
Delft University of Technology
Delft, The Netherlands

Joana Martins
j.martins@tudelft.nl
Delft University of Technology
Delft, The Netherlands

Elvin Karana
e.karana@tudelft.nl
Delft University of Technology
Delft, The Netherlands
Avans University of Applied Sciences
Breda, The Netherlands

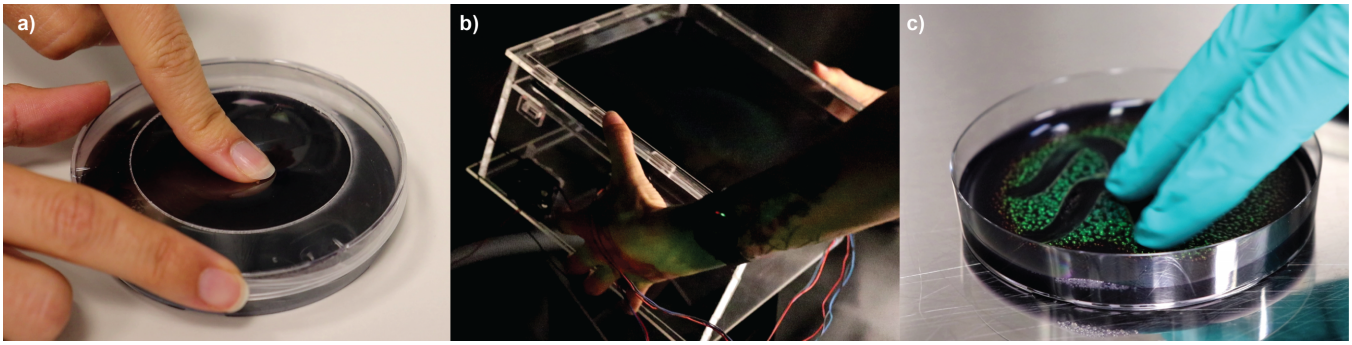

Figure 1: Direct interactions with Flavobacteria. a) (Re)activating living colour through pressing. b) (Re)directing living colour through tilting. c) (Re)arranging living colour through swiping.

ABSTRACT

HCI designers increasingly engage in the integration of microbes into artefacts, leveraging their distinct biological affordances for novel interactions. While in many explorations the interaction between humans and microbes is mediated, scholars also highlight the potential of direct interactions, such as visualising mechanical distortions or fostering a sense of relationality with nonhumans through eliciting intimate encounters. Seizing upon this potential, our study delves into the realm of direct interactions involving Flavobacteria, recently introduced as a colour-changing interactive medium in HCI. We present a design space for direct interactions where humans can (re)activate, (re)direct, and (re)arrange Flavobacteria's colourations, thereby fostering a personal and dynamic interplay between humans and microbes. With our work, we aspire to provide pathways and ignite inspiration among HCI designers to create living artefacts that cultivate active engagement and heightened attentiveness towards microbial worlds and beyond.

CHI '24, May 11–16, 2024, Honolulu, HI, USA

ACM ISBN 979-8-4007-0330-0/24/05
https://doi.org/10.1145/3613904.3642262

CCS CONCEPTS

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

KEYWORDS

Biological-HCI, Living Colour, Living Aesthetics, Human-Microbe Interactions, Direct Interactions, Flavobacteria

ACM Reference Format:
Clarice Risseeuw, Holly McQuillan, Joana Martins, and Elvin Karana. 2024. (Re)activate, (Re)direct, (Re)arrange: Exploring the Design Space of Direct Interactions with Flavobacteria. In *Proceedings of the CHI Conference on Human Factors in Computing Systems (CHI '24), May 11–16, 2024, Honolulu, HI, USA.* ACM, New York, NY, USA, 18 pages. https://doi.org/10.1145/3613904.3642262

1 INTRODUCTION

Driven by multiple factors, such as increased mediation via technology, a lack of access to natural spaces, and diminishing ecological literacy [62], human-nature interactions are increasingly scarce [6, 56, 76]. Ironically, this alienation comes at a time when human connectedness to nature is presented as a leverage point for two of the most pressing issues of modern times: the environmental crisis [1, 18] and human well-being [30].

Within HCI, the importance of designing for human well-being has long been recognised [9], while more recently scholars have also called for the widening of practices to navigate the complex

challenge of sustainability [17, 48, 68]. Demonstrating the potential to attend to both, biodesign approaches in HCI [40, 65] facilitate interactions with and draw our attention to the usually hidden world of microorganisms (e.g. [7]), which may yield benefits for ourselves and the wider natural world.

The integration of living microbes into interactive systems is a growing area of interest for HCI and design researchers. Organisms have, for example, been embedded in sensing devices [15, 53], ambient displays [14, 24], games [42, 70], and interactive installations [44, 45], in which novel functionalities and interaction possibilities are achieved through organisms' distinct biological affordances. In most of these interactive systems, interaction between humans and microorganisms is indirect, as human input is translated into a specific stimulus that is known to affect living microorganisms. Such mediation helps tackle challenges of control, accuracy, longevity, and bio-safety for interactive living systems [58, 66]. Yet, HCI designers show increasing interest in exploring more direct interactions with microbes, stressing their significance for establishing reciprocal relationships [33] towards a *culture of life* [3] instead of using microorganisms strictly as *controlled media* [60].

1.1 Direct Interactions with Living Microbes

The potential for profound connections with nonhuman entities through direct interactions between humans and living microorganisms has been widely acknowledged [7, 59, 60, 74]. These interactions foster intimate experiences that, in turn, amplify relational dynamics and empathy [26, 29], particularly when the intricate living aesthetics of microbes (i.e., their temporal expressions [33]) are perceivably influenced by human interactions. This relationality holds the potential to develop sensibilities for non-human temporalities and needs [61, 87], while affording reflection on our own everyday practices through a patina of *living traces* [23]. Ultimately, these reciprocal engagements hold potential for increased ecological awareness and a deeper appreciation for the intricate web of life that surrounds us [35]. Acknowledging the potential for intimate engagements facilitated by direct interactions with living microorganisms, our objective is to explore and dissect this design realm further. We initiate this exploration by explaining what we mean by 'direct interactions with microbes'. Given the relatively nascent nature of microbial-HCI [40] as a research endeavour, we adopted a broader perspective to screen through literature pertaining to direct interactions involving other living entities (i.e., plants) or entities with lifelike attributes (e.g., smart materials). This approach aided us in refining our description.

Looking first within the field of microbe-HCI, Ofer et al. [60] describe direct interactions as unmediated and physical interactions in which microbes respond to kinetic stimuli within designed environments. At the larger scale of living plant interfaces, Chang et al. [11] consider other inputs, in addition to touch, through which humans can directly interact with living organisms, for example, gestures and voice. Yet, by their definition, a direct interaction between plants and humans can be both locally situated in close proximity and occur remotely through a connected interface. In the context of shape-changing interfaces, Rasmussen et al. [69] classify direct interactions as those that employ shape-change as both input and output, which can again be experienced locally or remotely. Finally, we looked into Lim et al.'s [50] paper on interaction gestalt, which helped us get a better understanding of how interaction attributes, such as *directness* and *proximity*, can define direct interactions with microbes.

Drawing from these existing works in HCI and extensive discussions within our team, we have formulated the following definition to serve as a guiding framework for our research, as presented in this paper: **Direct interactions with microbes refer to instances where humans act upon living artefacts through their own bodies (e.g., touch, movement, voice, etc.), thereby inputting signals to microorganisms in an unmediated way. In response, these microorganisms adapt their behaviour, often manifesting changes in their living aesthetics (e.g., alterations in colour) that are perceivable by humans in close proximity.**

Given the immense potential inherent in direct interactions with microbes, it becomes evident that HCI stands to benefit from a design space outlining a comprehensive spectrum of possibilities within this context. With that aim, this research contributes to the HCI community by inspiring and outlining the possibilities of direct interactions with living microorganisms through our explorations with Flavobacteria. Recently introduced as a colour-changing interactive medium in HCI [23, 41], these bacteria show great variety in their colony's form, texture, and iridescent colour as well as in their stimuli response time (i.e., immediate and delayed) and are affected by direct human input. Specifically, our goal is to further explore direct interactions with Flavobacteria by (re)activating, (re)arranging, or (re)directing their living colour. Through this exploration and our in-depth discussion, including a reflection from an ecological perspective, we aim to provide inspiration to HCI designers, opening up new and innovative avenues for interacting not only with Flavobacteria but also with other microorganisms.

2 RELATED WORK

2.1 Human-Nature Engagement in HCI

Humans possess an innate affiliation - or biophilia [85] - with living systems, which fosters a deep sense of connection linked to improved mental health, stress reduction, and enhanced cognitive abilities [28, 47, 63, 64] . In addition to these positive effects on humans' well-being and functioning, nature engagement can increase our ecological awareness and sense of responsibility towards the natural world [12]. Yet, technological development in the industrialised world seems to have gradually removed people from nature [20, 82]. Digital technologies play a significant role in this phenomenon and therefore contribute to catastrophic effects such as human depression, loss of emotional affinity to nature, and a decline in pro-environmental attitudes and behaviours [56, 76].

Aiming to restore this balance, HCI researchers have identified many possibilities for public (re)engagement with nature through technologies [84], ranging in distance from nature (i.e., *in situ* versus *ex situ*) and in their *directness of experience* (i.e., directly or indirectly, e.g., through mediation). Mediated nature experiences allow for temporal compression of ecological processes and the capture of otherwise imperceptible phenomena, as, for example, Gaver et al.'s [21] DIY wildlife camera, which makes humans more aware of and ultimately concerned with local wildlife. Direct experiences, on the

other hand, might have a greater capacity for enriching encounters, fostering a deeper sense of connection and appreciation for nature. Researchers have, for example, explored how computation might help us connect to and care for nature through inspiring a new wave of forest technology [8].

Challenging the ingrained idea of an ontological separation between humans and nature, Haraway [26] introduced the notion of *natureculture*, which recognises that humans are deeply entangled in complex relationships with other species and ecosystems. Puig de la Bellacasa [16] further explores this idea by emphasising the ethical responsibilities and actions that arise from these interconnected *naturecultures*. Likewise, Escobar's work on *pluriversal* approaches [19] emphasises the significance of diverse worldviews and engagement with non-human entities. Tsing [80] amplifies the conversation by advocating for the recognition of agency within the realms of non-human actors—be they plants, animals, or microbes. Through this lens, we can develop more sustainable and inclusive approaches to environmental stewardship.

These concepts of ongoing interspecies entanglements have been adopted by HCI communities, shifting attention from a human-centred agenda to a multispecies worldview [81]. Researchers within this community challenge us, for example, to design for cohabitation [36, 75], engage in symbiotic encounters [52], and become more attentive towards the more-than-human world [48]. Rodgers et al. [72] presented an approach to imagining such sustainable futures, seeking to highlight relations between people and nonhuman stakeholders. Reflecting how interactive artefacts can open new pathways for noticing and engaging with other species, Liu et al. [51] have introduced the concept of *collaborative survival* within the context of mushroom foraging, which brings us to the field of microbe-HCI.

2.2 Human-Microbe Interaction in HCI

Focusing on the microscopic lifeforms of our natural world, designers and researchers within the field of bio-HCI [58, 66] explore the unique temporal qualities of microorganisms for novel interaction possibilities between humans and microbes. In the case of Liu et al.'s [51] multisensory tools for noticing fungi, humans are invited to interact with microbes *in situ* (i.e., at the microbe's original location). Numerous other concepts within microbe-HCI [40] concentrate on engaging with microbes outside their natural setting and incorporating them into interactive artefacts, which Merritt et al. [58] characterise as *living media interfaces*. Rafigh [24], for example, encompasses a living mushroom colony, motivating children to do speech exercises as data on usage of a digital app is used to regulate the interface's irrigation system.

Even though, in many of these instances, living microorganisms are mainly presented as *controlled media* [60], researchers increasingly promote the establishment of a *culture of life*, raising critical questions about mutualism, care, and cohabitation [3, 33, 60]. Zhou et al. [87] have, for example, introduced a temporal-aligning interface for timely noticing cyanobacteria behaviour, fostering reciprocal human-microbe relations in everyday scenarios. Ofer et al. [60] have delved into unmediated and physical interactions with bioluminescent algae while introducing an organism-centered approach to preserve the organism's livingness. Both of these works extend invitations for humans to engage in direct interactions with microbes, emphasising opportunities for more intimate and reciprocal relationships with them. This is particularly evident in the context of how humans can influence the *living aesthetics* [33] of microbes. Harnessing this opportunity, researchers have, for example, explored possibilities for visualising direct interactions (e.g., bending, twisting, and stretching) through encapsulating bioluminescent algae in soft chambers [46] and developed a DIY shaking device to explore diverse ways humans can provide direct input for living light output [4].

Zooming further into the design of living artefacts for direct interactions with microbes, Ofer et al. [60] distinguished open, porous, and closed environments to physically interact with bioluminescent algae. While a closed environment might be beneficial in safeguarding the well-being of microorganisms and enhancing our sense of safety and acceptance towards such living artefacts, it may potentially diminish the intimacy of the experience. Open environments, on the other hand, such as Nukabot [13], which invites humans to stir a symbiotic culture of microbes by hand on a daily basis, foster affective relationships between humans and microbes through physical contact. Along the same lines, a number of researchers have delved into the kombucha fermentation practices, wherein humans and nonhumans engage in a notably direct manner with one another in open environments. Researchers have, for example, investigated this practice as a platform to recognise relationality with nonhumans through collective reflection with kombucha brewers [74] or presented a range of probes for direct sensory engagement with this biofilm made by bacteria and yeast, aiming to reveal the interconnectedness between human- and nonhuman-designers [59].

Exploring another facet of the potential within direct interactions with microbes, Groutars and Risseeuw et al. [23] discussed how structurally coloured Flavobacteria can capture the peculiar ways in which humans interact with objects and spaces through their distinct temporal expressions, namely *living traces*. Besides insights on our own behaviour, such a patina of *living traces* offers a unique perspective on the intricate relationships between humans and the microbial world. Highlighting such relationships can aid in understanding that humans and nonhumans are inextricably interconnected.

Overall, the perceptibility and promptness of response have been discussed by researchers at times (e.g., [60]), highlighting the need to mediate the "output" of some microorganisms to effectively unveil shifts in their behaviour [41]. For example, the behaviour of Cyanobacteria was manifested through colour shifts in electrochromic material triggered by their photosynthetic activity [87]. Adopting digital avenues, the well-being of fermentation bacteria was translated into voice interactions and blinking patterns [13], while the electrons generated by microbial fuel cell biofilms enabled the creation of artistic animations [3]. Intervening in microbial responses can serve to address 'temporal dissonance' [87] between humans and microorganisms, aiding in exposing the well-being or struggles of microorganisms [41] for timely care practices. Nevertheless, excessive mediation might detract from the experience, much like the way unmediated interactions with nature in general tend to offer more enriching encounters than mediated ones [79].

2.3 Flavobacteria as an Interactive Medium

Flavobacteria species, in particular *Cellulophaga lytica*, have recently been introduced as an interactive living medium for HCI [23] due to their ability to produce dynamic colourations when growing on a surface (Fig. 2). These bacteria can organise their cells into so called photonic crystals [32, 38, 73], which interact with light and create striking visual effects akin to butterfly wings. While the exact reason behind this behaviour is, to date, unknown, microbiologists have revealed a lot of insights over the last decades on Flavobacteria's ability to self-organize. Those include the factors that affect this organisation, such as temperature [38, 83], different substrates [77] and the presence of other microbes [25], as well as the associated genetic pathways [32]. Doing so, they identify opportunities for engineering living optical materials such as sustainable paints and living sensors [32].

In the context of HCI, Groutars and Risseeuw et al. [23] explored Flavobacteria's temporal qualities and responsive behaviour, focusing on the changes in their expression, i.e., living aesthetics. They introduced various ways to tune Flavobacteria's living aesthetics, such as through environmental stimuli and "direct human input"- in which they explored different techniques of applying bacteria and physically altering the colonies' growth. This work highlights the potential of Flavobacteria for Living Colour Interfaces (LCIs), which can embody digital and environmental data as well as enable playful interactions with living media.

To further support HCI designers in exploring Flavobacteria's living aesthetics, Risseeuw et al. [71] presented FlavoMetrics, a digital tool that enables designers to virtually inoculate Flavobacteria and manipulate stimuli to tune the living colour in a digital environment. Kim et al. [41] explored how different mechanisms could aid in surfacing Flavobacteria's livingness towards timely noticing Flavobacteria's changes in behaviour and enriching how we interact with them.

Building upon the foundation laid by these HCI studies, we aim to elaborate on different ways to influence Flavobacteria's living aesthetics as well as further unpack direct interaction possibilities with these vividly coloured bacterial colonies. We believe Flavobacteria provides an exceptional case for exploring the landscape of direct interactions with microorganisms due to the striking transformations in their colony's form, texture, and iridescent colour. Furthermore, Flavobacteria exhibit a spectrum of response times to stimuli, including both immediate and delayed reactions, offering a rich design space for HCI designers, which we aim to commence with the initial set of explorations in our paper.

3 DESIGN SPACE OF DIRECT INTERACTIONS WITH FLAVOBACTERIA

3.1 Our Approach

Focusing on the distinct qualities of Flavobacteria, our research is guided by our curiosity and fascination with these microorganisms. Over the course of three years, we embraced a material-driven design approach [34], which prompted us to centre our attention on the distinct characteristics and affordances of these microorganisms while exploring potential user experiences and interactions. We started our explorations by carefully considering the microorganisms' needs and exploring their habitat elements [33, 60, 86]. In an attempt to open up the design space of directly engaging with these microorganisms, we then proceeded to explore Flavobacteria's unique colour-producing mechanism (i.e., structural colour as a means of cell organisation) and elements that affect their living aesthetics.

Our exploratory studies were conducted in our biolab at the TU Delft Faculty of Industrial Design Engineering, where we had access to specialised equipment for cultivating living microorganisms. We worked with *C. lytica* PLY A2, which we cultivated at room temperature. This non-pathogenic bacterium originates from marine environments and is known for its brilliant structural colourations [23, 37]. The habitat we designed to support Flavobacteria's growth included a semi-solid surface created with marine agar medium [23], enabling them to thrive and form optical structures. All the

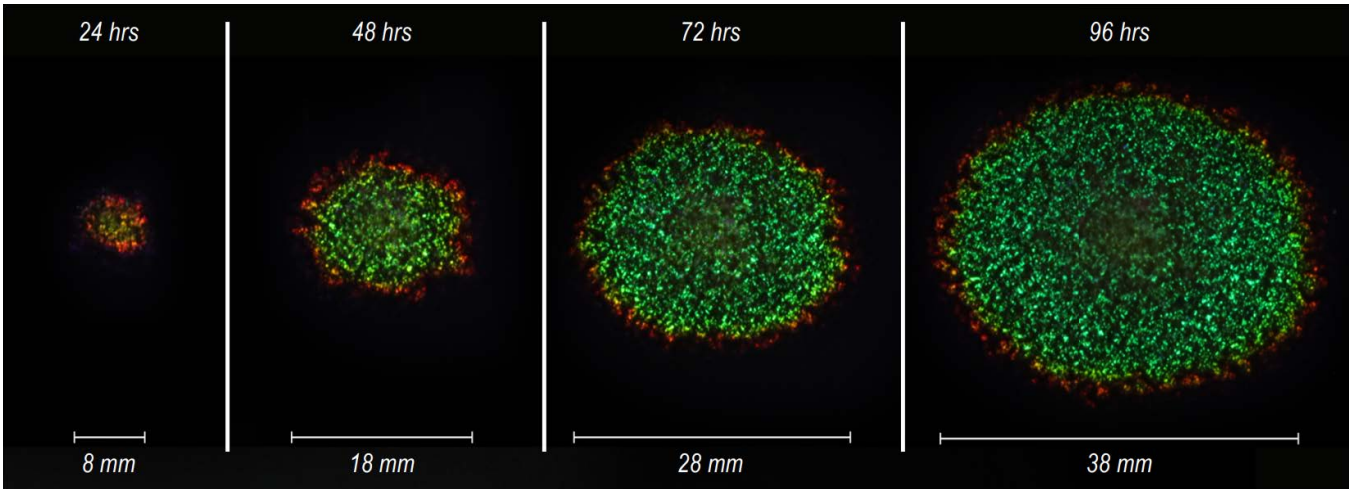

Figure 2: *Cellulophaga lytica*'s growth over four days, expanding around 5mm in radius a day and displaying a variety of colours, ranging from violet and red to more dominant green hues. Image credits: [71].

experiments were conducted with sample triplets for reliable results, except for one of our studies in Section 4 (as elaborated on in the discussion).

We used photography and videomaking to capture the living aesthetics of Flavobacteria in response to our direct interactions with them. This allowed us to reflect on the particular effects of these interactions on the microbes' behaviour and analyse the living aesthetics in terms of form, texture, and iridescent colour, leveraging the vocabulary introduced by Groutars and Risseeuw et al. [23]. We used a Canon EOS 250D camera equipped with a macro lens and ring flash and aimed for capturing the colonies with incident angle of 45° from which they have been shown to appear the most brilliant and multi-coloured [23].

We documented events in the biolab as well as our experiences when interacting with and observing the microorganisms. Through this documentation of the first author, we were able to record the nuances and intricacies of our personal experience while interacting with Flavobacteria in the three presented studies (see appendix A.1), which we used to support our application concept ideation.

3.2 Basic Habitat Architecture of Flavobacteria Artefacts

Living artefacts that integrate Flavobacteria consist of a habitat enclosure, the microorganism(s), and growth medium (Fig. 3). The **habitat enclosure** can vary in *shape* and *size* as well as in properties related to the material, such as *flexibility*, *porosity*, and *transparency*. Considering these properties and the desired interactions, designers can, for example, create a more open or closed environment [60] for the microorganism or tap into materials' performative qualities [10], for example, by creating a flexible habitat from silicone [23] to invite humans to bend the artefact. The **microorganism(s)** can vary in their *genotype* (i.e., which species or strain(s)), *culture condition* (i.e., active or dormant), as well as their *amount* and *distribution* within the habitat. Regarding the **growth medium**, the ideal *nutrition*, *salinity*, and *viscosity* highly depend on the species. The agar medium [23] used in this work, for example, provides the optimal amount of nutrients, salt, and agar for *C. lytica* to thrive and produce structural colour. Additionally, designers can vary the growth medium's *colour* (e.g., adding black pigment to highlight Flavobacteria's colour), *surface texture* (e.g., creating texture to steer Flavobacteria's growth [23]), and *volume*, which mainly influences the temporal scale of the living artefact.

3.3 Interaction Primitives for Direct Interactions with Flavobacteria

Acting upon Flavobacteria artefacts through their own bodies, humans can directly interact with Flavobacteria through different input mechanisms (i.e., stimuli that affect microorganisms' living colour). These include salinity, oxygen, nutrients, humidity, temperature, exposure to other microbes, and mechanical force (Fig. 4a). The first five were derived from considering the microorganisms' needs, resulting in a range for each of these stimuli that is essential for Flavobacteria's livingness and/or structural colour. The last two factors, exposure to other microbes and mechanical force, were deduced by considering Flavobacteria's responsive behaviour. Mechanical force, in particular, boasts a broad spectrum as an input

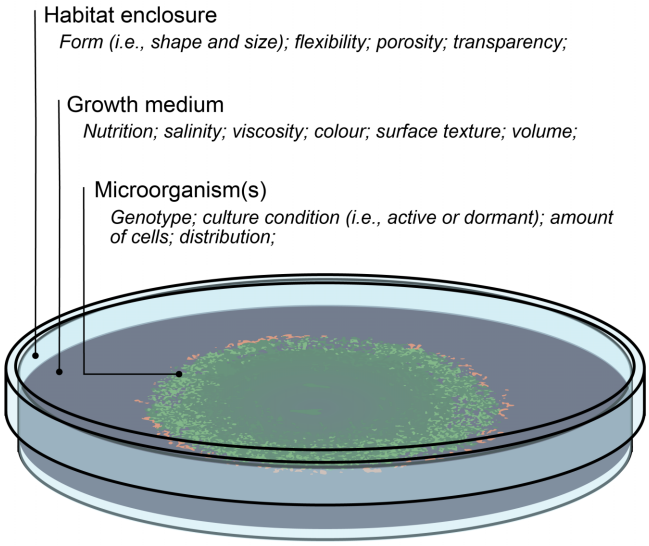

Figure 3: Basic habitat architecture and properties of Flavobacteria artefacts.

mechanism due to its capacity to physically interfere with Flavobacteria's optical structures as well as guide the bacteria to different conditions (e.g., nutrients).

Several examples of human input are included in the design space (Fig. 4b), which are categorised into body liquid and airflow, touch, and movement. The relationships between these human inputs and the input mechanisms are highly dependent on the basic habitat architecture. The porosity of the habitat enclosure, for example, influences whether touch allows Flavobacteria to interact with other microbes. We speculated on Flavobacteria's potential response to the examples of human input (visualised in Fig. 4b) based on prior works [23, 39] and our extensive experience with these microbes, yet none of these outputs had at this time been shown in a systematic study. This opens up an exciting research avenue for HCI, which we aim to inaugurate with the initial set of explorations in our paper.

3.4 Interaction Mechanisms

We distinguish three ways in which humans can interact with Flavobacteria's living colour: (re)activate, (re)direct, and (re)arrange. These are presented in Fig. 5.

Through the first interaction mechanism, humans can activate Flavobacteria's living colour as their input triggers the bacteria's cells to organise into optical structures that interact with incident light. This occurs when the necessary conditions for living colour are created as a result of the input, for example, when inoculating Flavobacteria from liquid freezer stock (-80°C) to moist, nutritious agar medium at room temperature. On a macro level, the resulting cell organisation over time culminates in the observable emergence of living colour. Upon the fading of iridescence over time, Flavobacteria's living colour can be reactivated by once again establishing the necessary conditions, in contrast with the prior assumption that Flavobacteria are dead as the iridescence fades away [23].

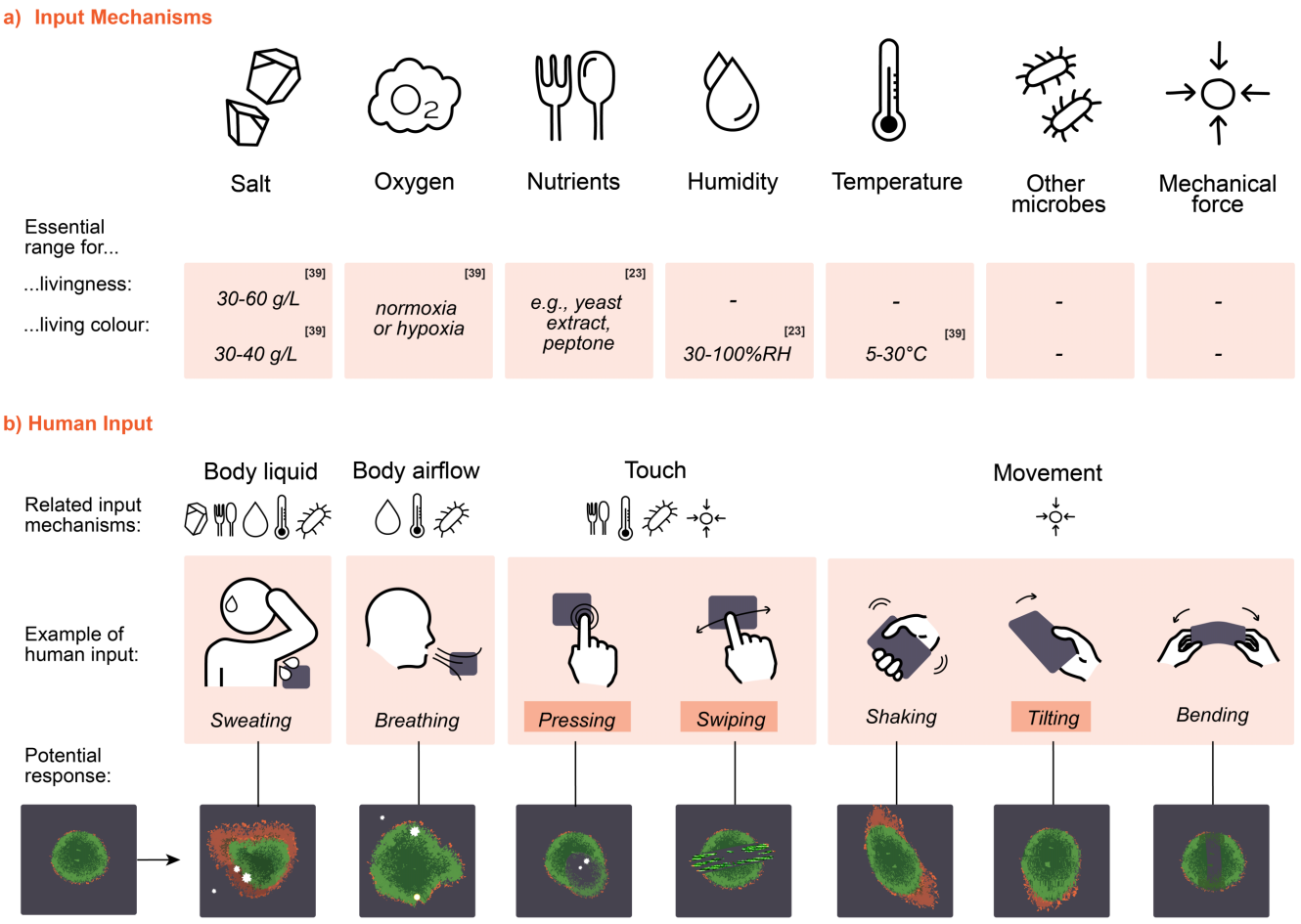

Figure 4: Interaction primitives for direct interactions with Flavobacteria. a) Input mechanisms, including the essential range of conditions for *C. lytica*'s livingness and living colour. b) Examples of human input with icons indicating their relation to the input mechanisms, red markings to show human inputs selected for further exploration, and Flavobacteria's potential response, in which white dots indicate other microbes.

Through the second interaction mechanism, Flavobacteria's living colour is (re)directed as input changes conditions, such as humidity [23], that affect how the cells organise themselves into optical structures. These changes prompt Flavobacteria to arrange their cells in a different way and/or expand their colony in a particular direction, leading to distinct changes in the colony's form, texture, and iridescent colour. Thirdly, humans can interact with Flavobacteria by (re)arranging their living colour. Here, the input physically interferes with the optical structures of the microorganisms, disrupting their cell organisation, upon which the cells will reorganise themselves in a different way over time. On a macro level, this results in the elimination of living colour and, later on, surprising colourations [23].

3.5 Selection of Interaction Primitives for Further Exploration

To illustrate how this design space can inspire a broad array of direct interactions, we selected three human actions to be further explored in our study, to either (re)activate, (re)direct, or (re)arrange Flavobacteria's living colour. We opted for the human actions of pressing, tilting, and swiping as they closely mirror the ways in which humans engage with everyday objects in HCI interactions (e.g., pressing buttons, tilting laptop screens, swiping touchscreens). Groutars and Risseeuw et al. [23] touched upon the effect of swiping movements that interfere with Flavobacteria's optical structures. Nevertheless, the microorganisms' response had not been fully explored, triggering our interest and curiosity. Besides, we were inspired by previous observations of Flavobacteria growing in a static vertical habitat [23] prompting our interest to investigate how tilting as a human action can (re)direct Flavobacteria's living colour.

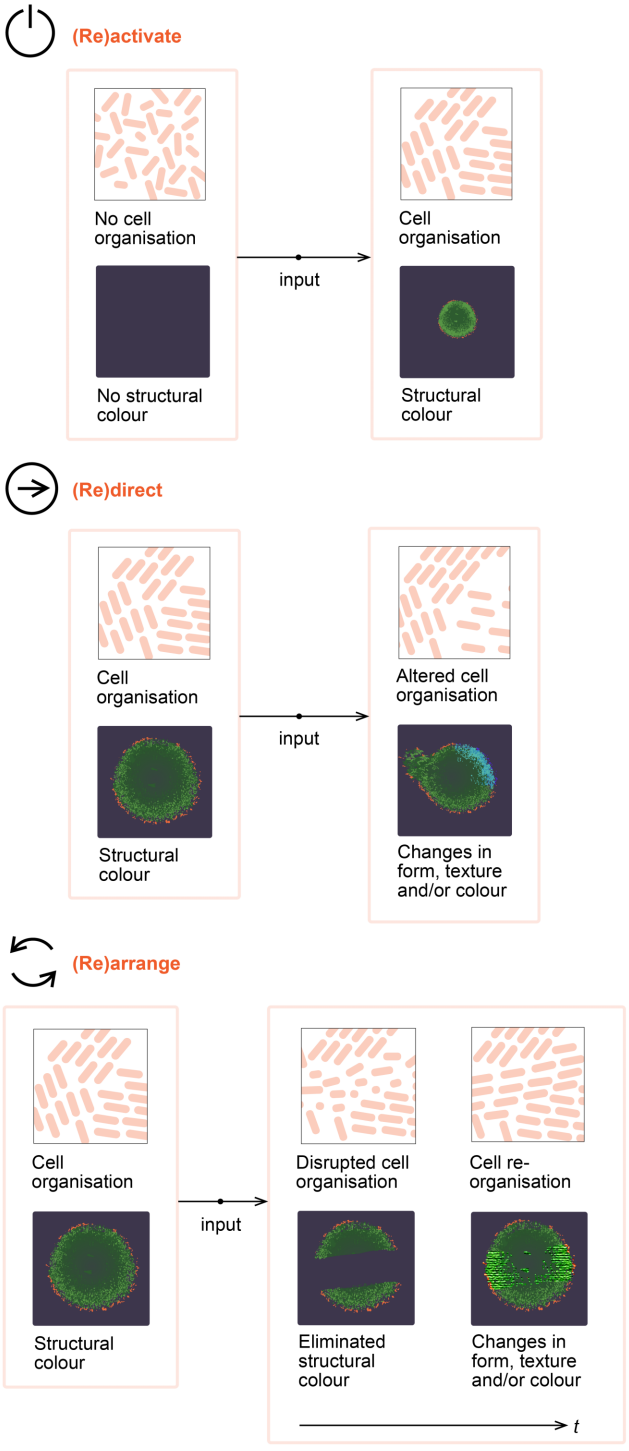

Figure 5: Mechanisms for interacting with Flavobacteria's living colour: (re)activate, (re)direct, and (re)arrange, showing changes on the micro (top) and macro (bottom) levels.

4 THREE STUDIES INTO DIRECT INTERACTIONS WITH FLAVOBACTERIA

In this section, we present our three lab studies in which we explored direct interactions to (re)activate, (re)direct, and (re)arrange Flavobacteria's living colour. We investigated Flavobacteria's response in relation to the human inputs of *pressing*, *tilting*, and *swiping*, aiming to identify the changes in the microbes' living aesthetics. For bio-safety reasons, we focused on the input mechanism of mechanical force only (i.e., not including the effect of other microbes). Focusing on one input mechanism at a time enabled us to get a better understanding of the input and output relations. Although the following three studies all revolve around the same input mechanism, they distinctly showcase the diverse spectrum of direct interactions it facilitates with Flavobacteria. We discuss the interaction procedure and the response of Flavobacteria for each study in detail, as well as potential HCI applications.

4.1 Study 1: (Re)activating through Pressing

4.1.1 Procedure. For our explorations into (re)activating Flavobacteria's living colour through pressing, a standard-sized Petri dish with agar medium was used as a habitat. We designed a flexible lid by laser cutting a hole in the standard rigid lid and sealing it with thin plastic foil. After sterilising the flexible lid with UV light, Flavobacteria were applied to the inside surface of the plastic foil. To extend bacterial survival in this environment without nutrients, Flavobacteria were first induced into a dormant state through lyophilization. This method, also called freeze-drying and commonly used in microbiology, inhibits microbial growth by removing water from the culture under low pressure. To protect the bacterial cells during this process, we first suspended them in a solution with a protective agent (i.e., sucrose).

The experiment of the *pressing* study consisted of two parts (Fig. 6). In the first part, aimed at *activating* Flavobacteria's living colour, dormant bacteria were exposed to agar medium to rehydrate and revive them. To do so, pressure was applied to the flexible lid until the Flavobacteria touched the nutritious, semi-solid surface (Fig. 7), mimicking the gentle touch of the inoculation process. In the second part, seven days later, Flavobacteria's living colour was *reactivated* by providing new territory to the colonies as they began to lose their iridescence. When preparing the habitat for this study, different compartments were made in the agar medium using circular cookie cutters. This allowed us to build a barrier, created by a small channel, ensuring that the bacteria initially only expanded within the first area. When the first area was colonised and faded in colour, pressure was once again applied to the centre of the flexible lid, allowing the bacteria to cross the channel and produce structural colour again in the new territory.

4.1.2 Response of Flavobacteria. After activation, Flavobacteria produced a familiar colony, i.e., expanding in a circular shape, ranging in colour from violet and red to more dominant green hues. However, whereas structural colour typically becomes apparent within 24 hours after inoculation, the colourful colony did not emerge until two days later (Fig. 8). This is probably due to adaptation to new conditions. The colony expanded until it reached the small channel in the agar medium on day 5 and obtained a more

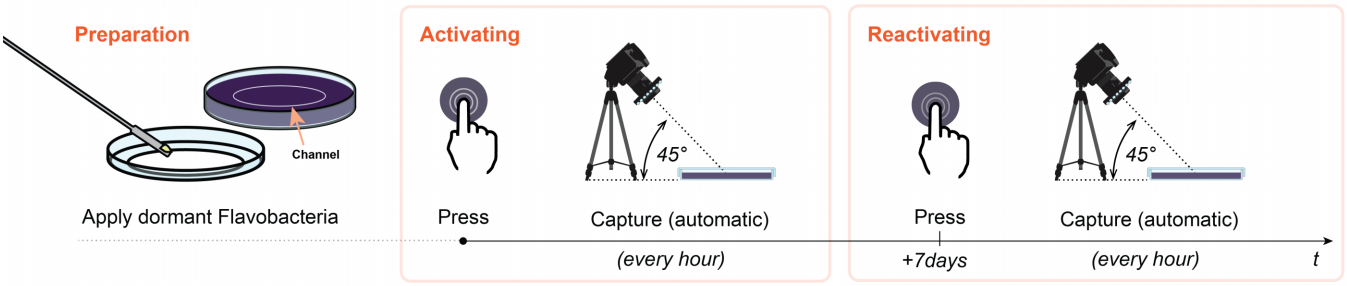

Figure 6: Illustrated procedure of the *pressing* study.

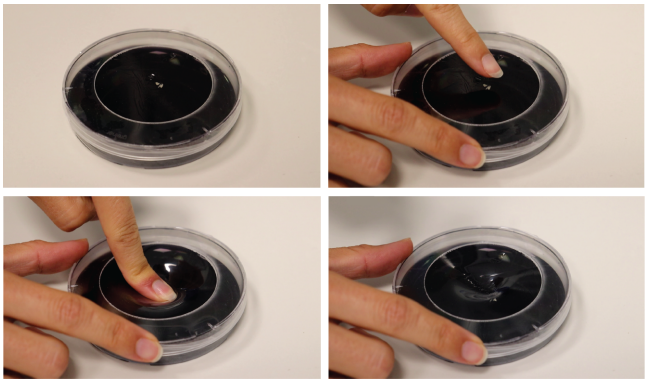

Figure 7: Applying pressure to the lid to activate Flavobacteria's living colour.

hollow shape over time as its iridescence gradually faded away from the centre. After applying pressure for the second time, seven days after activation, we could see Flavobacteria adhering to the plastic foil through their inherent yellow pigment [67] (Fig. 9).

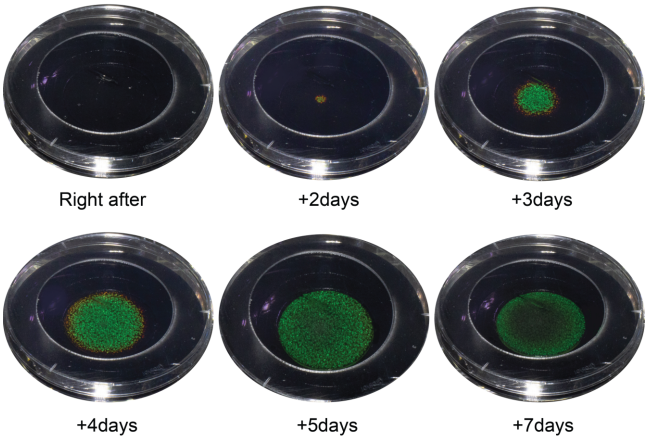

Figure 8: Overview of Flavobacteria's living colour after activation. See Appendix A.2 for details on the camera setup and the complete overview of images.

Figure 9: Flavobacteria on the plastic foil after applying pressure to reactive their colour.

Five hours after the reactivation, it became apparent that Flavobacteria started producing structural colourations in new areas (Fig. 10). Again, the colony's texture and iridescent colour developed in familiar ways. However, the form was no longer circular because the bacteria were irregularly pushed to the new area, initially forming separate colonies that seemed to merge over time.

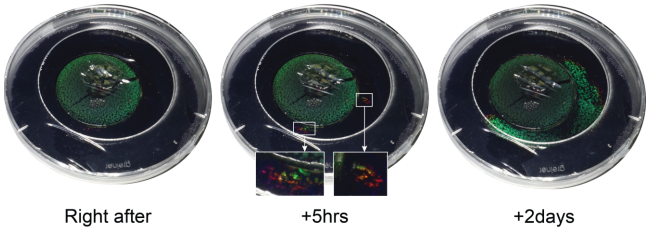

Figure 10: Overview of Flavobacteria's living colour after reactivation, with close-ups showing first signs of structural colour after five hours. See Appendix A.2 for details on the camera setup and the complete overview of images.

4.2 (Re)directing through Tilting

4.2.1 Procedure. Flavobacteria's living colour is affected by the orientation of the agar medium, as can be concluded from initial observations of growth in a vertical habitat presented in [23]. Yet, this responsive behaviour only comes to light on a large spatial and temporal scale. For our explorations into (re)directing Flavobacteria's living colour through tilting, we therefore created an environment

for the microorganisms to thrive for up to one month. The habitats (Fig. 11) offered a 240 mm by 240 mm surface of agar medium and a relative humidity of 95% to ensure hydration. In prior work [23], the habitat was tilted 90 degrees, yet we wondered whether a smaller tilt - which could be the case in everyday interactions with HCI objects - would be adequate to affect Flavobacteria's growth. We opted for 45 degrees and lasercut a base to support tilting the habitat.

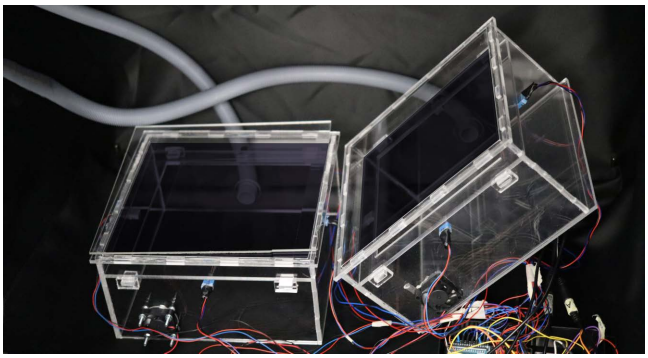

Figure 11: Two custom-made habitats for the *tilting* study. Image shows setup of the first experiment on day 1.

The first experiment of this exploration (Fig. 12a) evolved around *directing* Flavobacteria's living colour in a certain direction. The bacteria were inoculated in the designed habitat, which, one hour later, after allowing the Flavobacteria culture to settle, was tilted 45 degrees by carefully placing it on the base. Flavobacteria were also inoculated in a second habitat, which was placed in a horizontal position, as a control group.

In the second experiment (Fig. 12b), our aim was to *redirect* Flavobacteria's living colour. This time, both habitats were tilted 45 degrees one hour after inoculation. After six days of growth - when there was still plenty of available agar medium for bacterial growth - one of the habitats was carefully flipped the other way (Fig. 13).

As it proved challenging to capture Flavobacteria's iridescent colour in both habitats simultaneously, the automated camera was only used to extensively capture the microorganisms that we interacted with (in experiment 1) or those we interacted with repeatedly (in experiment 2). It was positioned at an approximate 45° angle with the habitat surface (see left image of Fig. 13) to capture the distinctively brilliant colours of the colony. To analyse differences between the colonies, both habitats were also captured manually from the same angle and distance (i.e., circa 30cm) every weekday.

4.2.2 Response of Flavobacteria. In the first experiment, colonies in the tilted and horizontal habitats displayed remarkable differences in their texture and form, proving that a tilt of 45 degrees was adequate to affect Flavobacteria's growth. As can be seen in Fig. 14, Flavobacteria in the tilted habitat created different colony textures in the top and bottom areas, whereas bacteria in the horizontal habitat demonstrated a more uniform texture. Only six days after the tilting movement, these subtle differences in texture became noticeable.

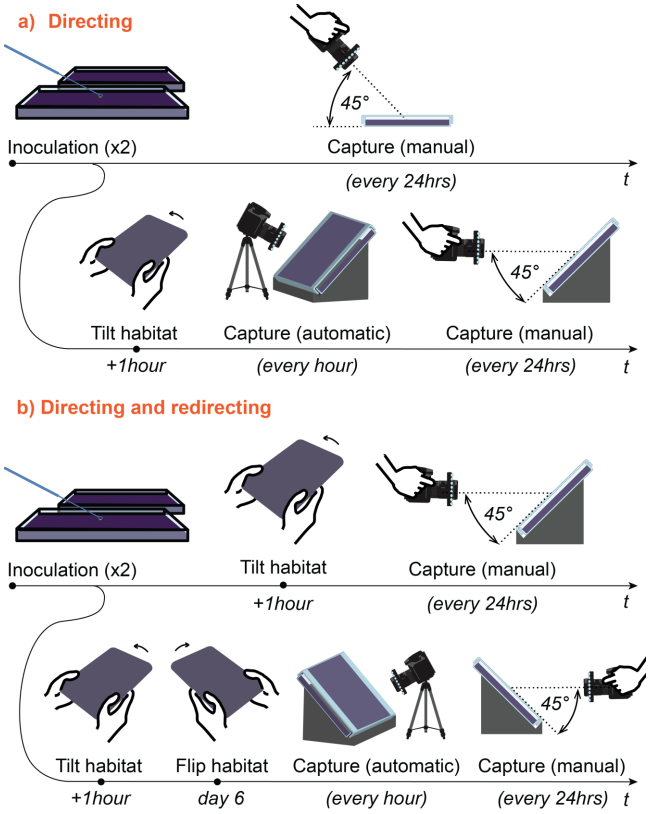

Figure 12: Illustrated procedures of the *tilting* study's first (a) and second (b) experiments.

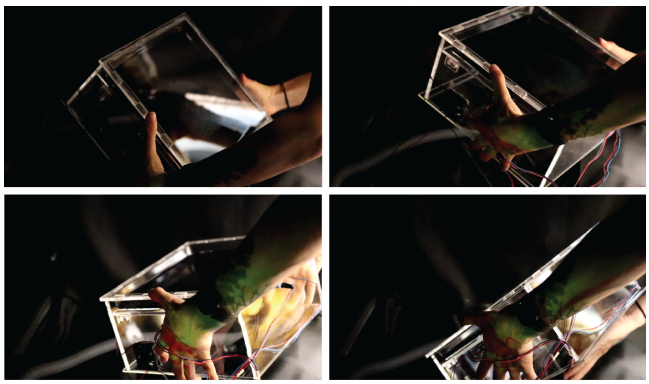

Figure 13: Flipping the habitat on day 6 during the second experiment, captured with the automated camera.

The overview in Fig. 15 shows how the colonies further developed over time, illustrating the difference in the colonies' form, which becomes noticeable around days 7/8. Whereas bacteria in the tilted habitat managed to extend their colourful colony to the bottom edge of the habitat in nine days, bacteria in the horizontally-orientated habitat only started to reach the edges around day 15. At this time, the bacteria in the tilted habitat also reached the top

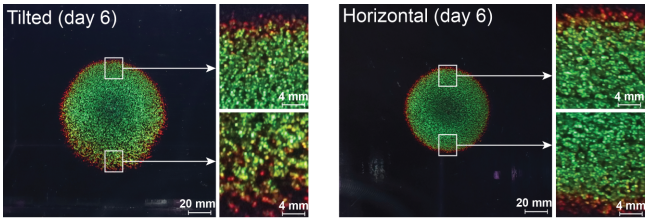

Figure 14: Texture differences between Flavobacteria's living colour in the tilted (left) and horizontal (right) habitats on the sixth day of growth. Pictures are perspective-corrected and 5x magnified in closeups on the right.

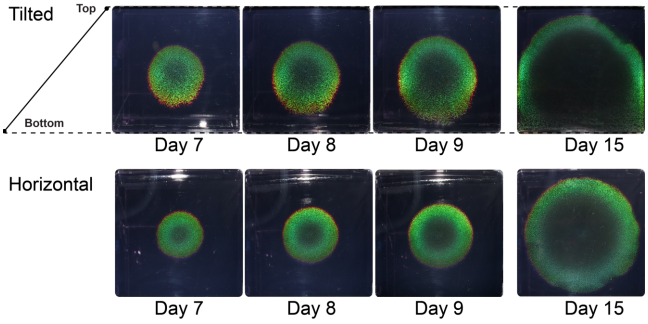

Figure 15: Overview of Flavobacteria's growth in the tilted (top) and horizontal (bottom) habitats, showing perspective-corrected images. See Appendix A.3 for details on the camera setup and the complete overview of images.

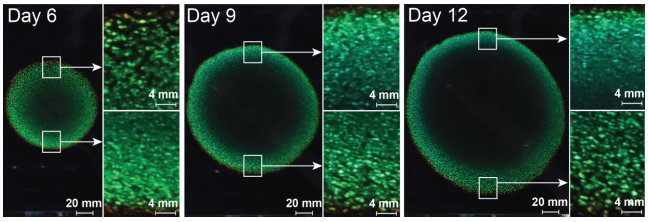

Figure 16: Adjustment of texture differences within the flipped colony. The picture on day 6 was taken immediately after flipping. Pictures are perspective-corrected and 5x magnified in closeups on the right.

part of their habitat. These differences in colonies' texture and form are probably caused by the moisture that escapes from the agar medium [2], easing the microbes' gliding motility in a downward direction.

In the second experiment, both colonies demonstrated similar differences in texture between the top and bottom areas (as seen in the first experiment) until one habitat was flipped on day 6. Over the following six days, new bacteria in the flipped colony started to form structural colour correspondingly: the (now) bottom area started to show a more *scattered* texture, while the (now) top area transformed to a *dense* texture (Fig. 16).

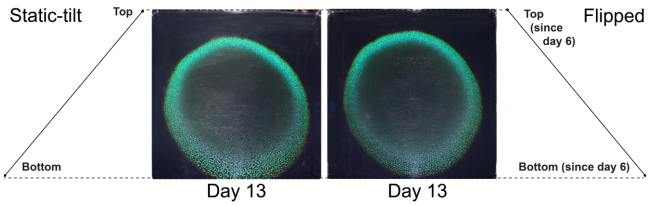

Figure 17: Flavobacteria's perspective-corrected growth in the static-tilted (left) and flipped (right) habitats, illustrating how the static-tilted colony (left) hit the bottom of its habitat first. See Appendix A.3 for details on the camera setup and the complete overview of images.

Whereas the static-tilted colony was the first to hit the bottom of its habitat, the flipped colony started to adjust its form to its new orientation in a similar manner over time (see Fig. 17).

4.3 Study 3: (Re)arranging through Swiping

4.3.1 Procedure. For these explorations into (re)arranging Flavobacteria's living colour through swiping movements, we used a standard-sized Petri dish with agar medium as a habitat. Contrary to the first study, we did not opt for a flexible plastic foil as a lid, as bacteria adhering to it might compromise our observations of Flavobacteria's response. Instead, we performed the swiping in a sterile environment within the biolab (i.e., a laminar airflow cabinet), wearing a sterile glove to separate Flavobacteria from the human microbiome.

The first experiment of this exploration (Fig. 18a) evolved around *arranging* Flavobacteria's living colour. Here, we interacted with the bacteria by swiping only once (Fig. 19), three days after inoculation.

In the second experiment (Fig. 18b), the same swiping movement was repeated five times with an interval of 30 minutes. Again, this interaction took place three days after inoculation.

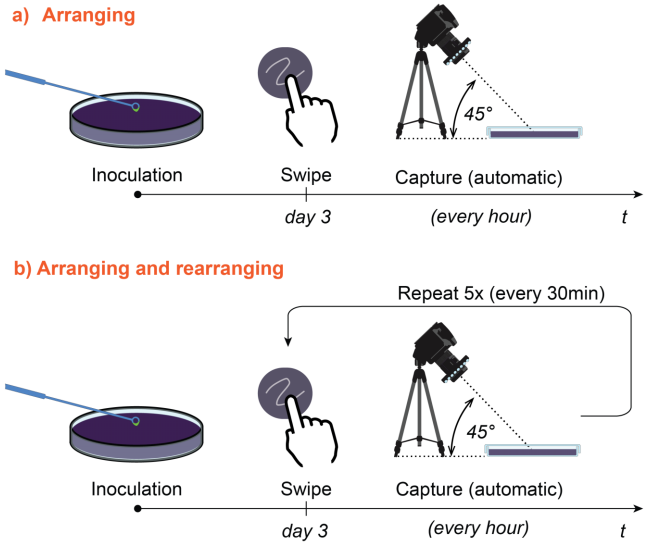

Figure 18: Illustrated procedure of the *swiping* study's first (a) and second (b) experiments.

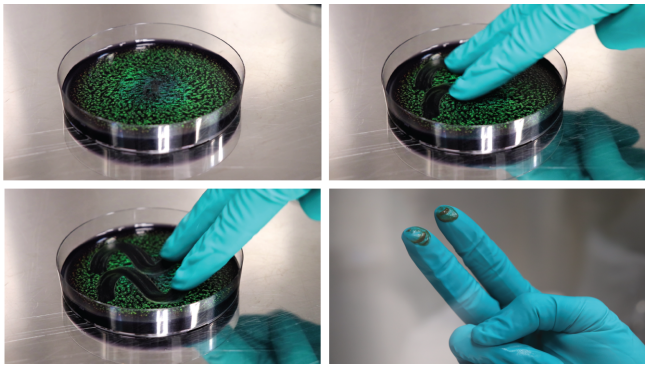

Figure 19: Swiping the bacteria on day 3. As can be seen in the left image, the colony's growth is remarkably advanced for the third day, which was caused by a heat wave over the weekend. The right image shows some transference of Flavobacteria to the glove.

Iridescent Flavobacteria are known to re-organize their cells when their organisation, producing structural colour, is interfered with [23]. However, we were unsure how quickly this response could be observed by the naked eye. In our first attempt to understand this response time, capturing Flavobacteria with a commonly-used time interval of one hour proved - to our surprise- not to be frequent enough to capture the first signs of response. With further testing, a time interval of 10 minutes was selected for the rest of our experiments.

To get a better understanding of the effect of swiping on the colony's iridescent properties, we additionally captured a sample from several angles- before and 30 minutes after swiping- using a custom-made tool (based on [23]).

4.3.2 Response of Flavobacteria. Flavobacteria's iridescent colour is instantly eliminated when swiping through the optical structures (Fig. 19), as the cell organization is disrupted. Colourations in these areas noticeably re-appear after 20 minutes and become clearer over time (Fig. 20). After swiping, the affected areas no longer exhibit a pointillistic texture but instead show a very uniform, remarkable colour, which is observable from specific angles (Fig. 21). This observed phenomenon likely results from the swiping movement aligning all cells in the direction of the motion, thereby influencing their reorganization.

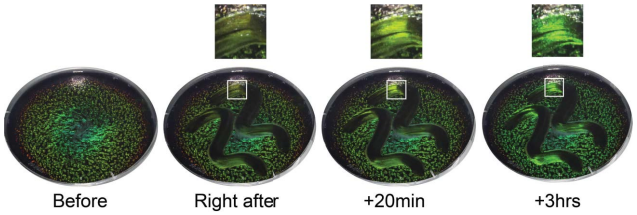

Figure 20: Overview of Flavobacteria's response to swiping movements over time, including a close-up showing the uniform texture after swiping. See Appendix A.4 for details on the camera setup and complete overview of images.

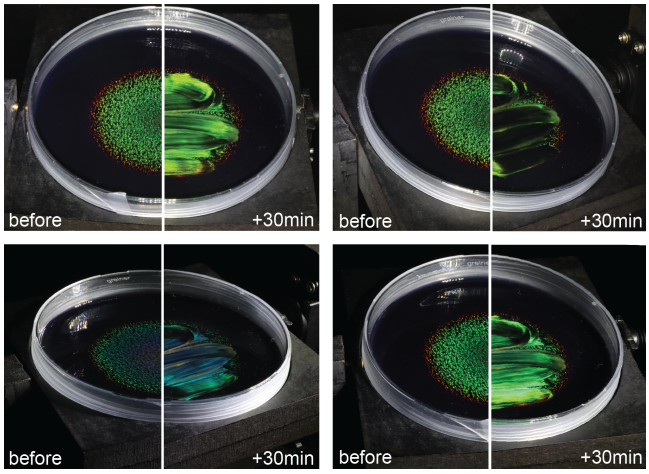

Figure 21: A colony of Flavobacteria captured from different angles before and 30 minutes after a swiping movement, demonstrating the effect of swiping on the colony's texture and iridescent colour. See Appendix A.4 for details on the camera setup.

During the second experiment, in which we interacted with Flavobacteria up to five times, the bacteria persistently reorganised into optical structures, recolouring the swiped areas (Fig. 22). Yet, some areas (as indicated in Fig. 22) exhibited less vivid colour over time.

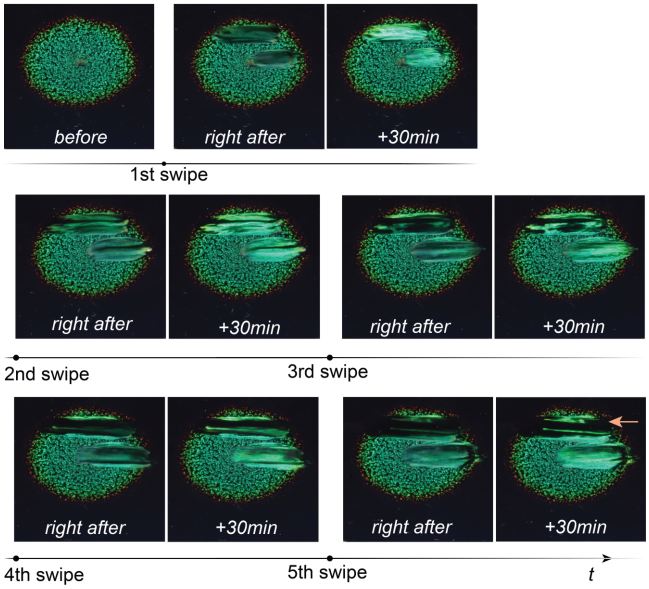

Figure 22: Overview of Flavobacteria's response to repeating swiping movements, showing a colony before, right after, and 30 minutes after each swiping. The arrow indicates the area that exhibited less structural colour over time. See Appendix A.4 for details on the camera setup.

4.4 Application Concepts

Our explorations into direct interactions with Flavobacteria through pressing, tilting, and swiping highlight their potential to act as a *qualitative display* [54] through a diverse range of grown patina affected by human input, i.e., *living traces* [23]. This potential can be harnessed to invite humans to reflect on everyday practices while building awareness and sensitivities towards Flavobacteria's unique temporalities, needs, aesthetics, and conditions in shared habitats. Below, we present three application concepts to ignite novel research directions in this context.

In our concept *FlavoToile* (Fig. 23), Flavobacteria are integrated into a dress, foregrounding the history between humans and their garments. This could enhance emotional attachment as well as provide insights into our body posture for better self-care practices through empathy towards microbes. Additionally, Flavobacteria's living colour can elevate the aesthetic appeal of these garments, adding a unique and artistic element to the wearables while also encouraging individuals to develop sensibilities towards microbes and embrace the integration of nature in their daily lives.

Figure 23: Visualisation of our concept *FlavoToile*. a) A kid asking for attention of the mother by touching her dress, thereby unintentionally (re)arranging Flavobacteria's living colour. b) Flavobacteria revealing the touch as their living colour is instantly eliminated.

On a larger scale, direct interactions with Flavobacteria could capture the peculiar ways that people interact with their surroundings. In our concept, *FlavoTread* (Fig. 24), the pressure from the footsteps of people walking through a public space activates Flavobacteria's living colour. Similar to the Drift Table [22], such an artistic, interactive surface could support *ludic engagement* in the everyday, driven by curiosity, exploration, and reflection rather than predefined tasks. It will bring a highly artistic element to public spaces and encourage people to notice, acknowledge, and reflect upon the temporal beauty that the microbes of our natural world have to offer. Additionally, the performative, dynamic interplay in which humans can activate and reactivate Flavobacteria's colour in *FlavoTread* invites humans to seek out unexplored areas in shared habitats while providing new territory to the bacteria, which prompts reflection on their caregiving practices for nonhumans.

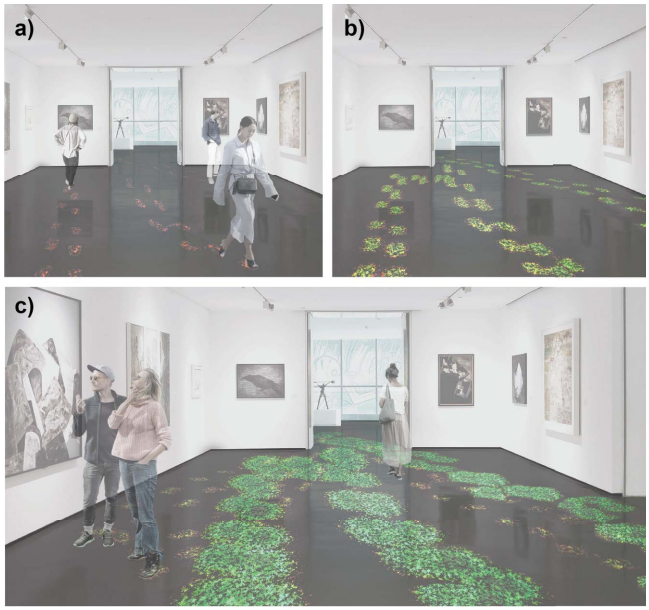

Figure 24: Visualisation of our concept *FlavoTread*. a) People activating Flavobacteria's living colour through their pressing footsteps. b) Flavobacteria's growth over night. c) Flavobacteria revealing how people interact with a public space and inviting people to explore new areas as well as provide new territory to them. The colonies in these visualisations were simulated using FlavoMetrics [71].

Flavobacteria's temporal response to humans' direct input could also foster mindful interactions. For example, by marking the start of a work break with a swipe that disrupts the structural colour, mental well-being could be supported as Flavobacteria's response over the next twenty minutes is patiently observed. This intentional interaction with Flavobacteria's optical structures could serve as a meditative practice, allowing individuals to focus their attention and find a sense of calm in the mesmerising colourations. In contrast to the relatively fast response to swiping, Flavobacteria respond to tilt in a particularly slow manner, highlighting their potential to enhance mindfulness by revealing the passing of time in an abstract manner. In our concept *FlavoTempo* (Fig. 25), the slow changes in Flavobacteria's living aesthetics in response to tilt create a unique and intriguing visual representation of time passing, akin to an hourglass, allowing individuals to develop a deeper understanding of the concept of time and its relationship to their daily activities.

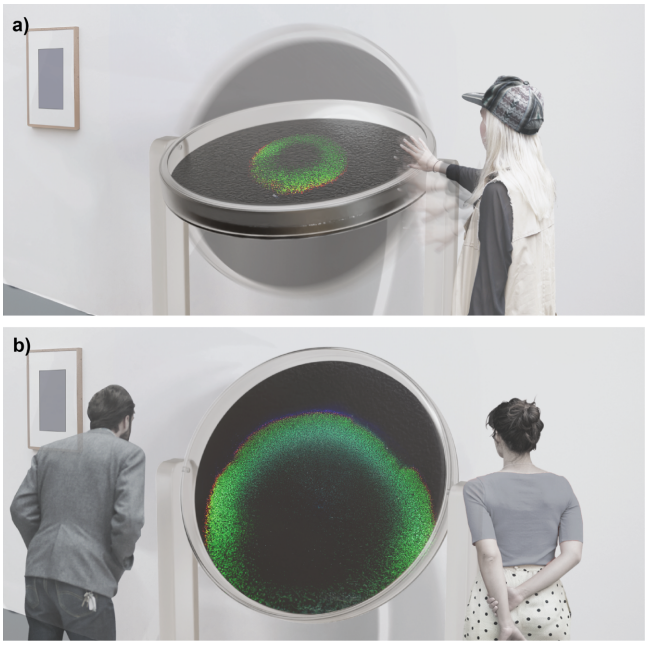

Figure 25: Visualisation of our concept *FlavoTempo*. a) A person tilting the artefact, thereby directing Flavobacteria's living colour. b) People observing how Flavobacteria reveal the passing of time in an abstract manner in response to tilting movements.

5 DISCUSSION

This paper expands on the notion of direct interactions with microorganisms in living artefacts, providing HCI designers with a design space that explores (re)activating, (re)directing, and (re)arranging Flavobacteria's colourations in this context, supported by application concepts. In this section, we reflect on the complexities and opportunities that emerged from this research, discuss the further implications of direct interactions with microbes for HCI, and address the limitations of our study.

5.1 The Nature of Direct Interactions with Microbes

While our explorations diversified the range of possible interactions with Flavobacteria, we struggled to define what we meant by direct interactions with microbes. Our comprehension of the boundary separating indirect from direct interactions in this context evolved as we explored related definitions and existing living artefacts. Yet, some cases left us with more confusion than clarity, such as the Living Light [49]. Here, humans physically touch a plant to activate a light, which is powered by microbes in the soil that release electrons while interacting with the plant. In this case, human input is mediated as motion sensors detect humans' touch, and the behaviour of microbes is not affected by this input. Yet, the interaction can be experienced as a direct one, as humans might not be aware of the living artefact's working principle. Such examples lead us to believe that the threshold between indirect and direct interactions with microorganisms in the real world is, in fact, blurred, and linked to human experience rather than discrete boundaries. Nevertheless, to narrow the scope of this work and guide our explorations, we have formulated a definition that aims to differentiate indirect and direct interactions with microorganisms. While our scope for direct interactions excludes both mediating human input to affect microorganisms and the remote experiencing of microorganisms' responses, there still exists a spectrum of direct interactions in which both mediation and proximity play important roles.

5.1.1 Mediation-Related Opportunities and Dilemmas. Considering our definition of direct interactions, microbes adapt their behaviour in response to unmediated human input. Nevertheless, mediation is sometimes needed to effectively reveal shifts in their behaviour. This is especially relevant when microbial responses remain entirely imperceivable to humans or occur so slowly that we either lose interest or are too late to prevent harm to the microorganisms. The methods of mediating microbial responses exhibit significant variation. For instance, mediating these responses may involve extensive translation, such as when fermentation bacteria's activity is conveyed through voice interaction [13] or electrons generated by biofilms bring forward artistic animations [3]. In contrast, other cases might offer more natural ways to reveal the responses of living organisms through, for example, the magnification of cell movements (e.g., [43]) or the temporal alignment of colour-changes in the living interface through non-digital mediation, which humans may not even be aware of [87]. As Flavobacteria have distinct living aesthetics, exhibiting visual changes in their colony's form, texture, and iridescent colour, mediation of their output is not strictly *necessary*, allowing us to position our studies at the least mediated end of the spectrum.

5.1.2 Proximity-Related Opportunities and Dilemmas. Within our scope of direct interactions, humans provide input to microorganisms by acting upon living artefacts through their own bodies. Yet, the distance between humans and microbes themselves can vary extensively. The closest proximity of input for these interactions would involve humans touching microorganisms without any barrier in-between. Such direct interactions with microbes can facilitate microbial transfer, which, in the case of Nukabot [13] personally enriches the flavour of pickles, or can allow for the decomposition of human remains in the case of a living mycelium coffin [55], promoting biodiversity and circularity. However, due to bio-safety reasons and to maintain the integrity of microorganisms (e.g., by protecting them from dehydration or contamination), physical barriers may be necessary. In the *tilting* study, we used such a barrier and interacted with Flavobacteria by tilting their rigid habitat, as also shown in the *FlavoTempo* concept. Alternatively, touching microbes through a thin glove or plastic foil retains close proximity and provides a sense of intimacy (like in our concept *FlavoToile*)- perhaps so intimate that people are resistant to interacting with microorganisms in such a direct manner. *C. lytica*'s non-pathogenicity allowed us to move towards the close-proximity end of the spectrum. However, not all microorganisms are suitable for this [5], and close proximity with microbes is not always desired by default. Therefore, we call for designers to carefully consider both microorganisms and human needs and tune proximity as well as mediation of microbial responses for the desired outcome.

5.2 Challenges and Opportunities of Direct Interactions with Microbes for HCI

5.2.1 Diverse Temporalities of Microbes. Microorganisms exhibit a wide spectrum of temporal behaviours, ranging from immediate to gradual responses, presenting both challenges and opportunities for HCI designers. Slow microbial responses can encourage human mindfulness and reflection but, in extreme cases, may be considered a technical constraint [41], demanding excessive patience from humans to attend to microorganisms' temporality. They can even diminish the interaction effect [60] and the sense of reciprocity [33], as humans might no longer be aware that microbes are adapting their behaviour in response to their input. However, to a certain extent, delayed responses can enhance human curiosity, captivation, and emotional investment in microorganisms, fostering deeper engagement and creating a strong sense of connection towards profoundly meaningful relationships, as instantiated in our application concepts.

Comprehending these distinct temporal behaviours is crucial for designers of living artefacts, allowing them to tailor the temporal scale of the artefact and consider aligning human-microbe temporalities for timely care practices [87]. Yet, understanding these diverse temporal behaviours is challenging due to the different circadian rhythms and growth rates among them [57], as well as their ability to adjust these temporal behaviours based on various inputs. As demonstrated in our studies, Flavobacteria take six days to respond noticeably to tilting movements, while swiping elicits an immediate change in their living aesthetics. While offering a rich design space for HCI, this diversity makes predicting response times to certain inputs challenging, even with years of expertise in a specific microorganism, as shown by our initial attempt to capture Flavobacteria's response to swiping movements with a one-hour time interval.

5.2.2 Complex and Unpredictable Microbial Behaviour. As we move further away from interactions in lab environments and the mediation of input to regulate living systems, we enter a realm of (semi)open habitats [60] with less human control. Here, multiple input mechanisms can be in play, complicating our understanding of microbes' responses to certain inputs. For example, as illustrated in our design space, sweating can potentially affect salinity, nutrition, humidity, temperature, and the presence of other microbes. Such a single human input can lead to a wide variety in microbes' responses, as even subtle differences in microbes' environments can drastically affect their growth. For instance, in one of our studies, Flavobacteria's growth occurred twice as fast as usual due to high temperatures over the weekend. Whereas the interconnectedness of input mechanisms complicates the understanding of microbial responses, designers can also tap into this as an opportunity to create a dynamic interplay between human input and the diverse and unexpected living aesthetics of microbes.

Even in relatively controlled habitats, unexpected behaviour by microbes may occur. Our *tilting* study revealed unanticipated microbial behaviour in our first attempt to explore the effect of tilt (Fig. 26). Though grappling with the explanation of emergent behaviour was initially challenging, it sparked a fruitful discussion within our team about the level of control we should aim for. The emergent behaviour that comes from working with living entities poses challenges and questions for designers regarding how we should design in light of the unpredictabilities of microbes and how this unpredictability is experienced by humans interacting with living artefacts.

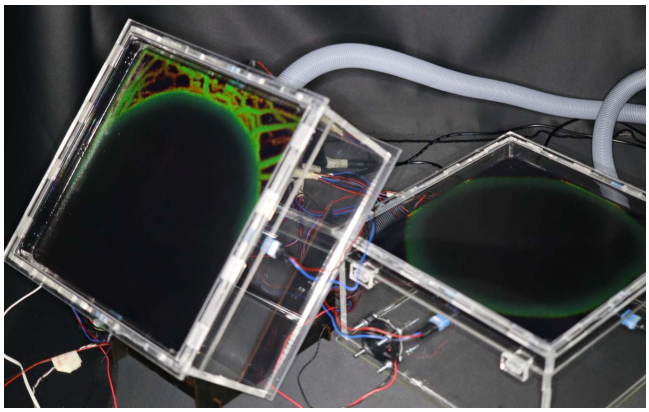

Figure 26: Flavobacteria's unanticipated behaviour in the first attempt to explore the effect of tilt. On day 14 of the experiment, bacteria in the colony created different paths that went in all directions across the available agar medium in the top part of the habitat.

5.2.3 Bio-Safety of Direct Interactions. As discussed by diverse scholars in Bio-HCI (e.g., [23, 60]), it is challenging to design an appropriate habitat for microorganisms that preserves their livingness outside lab environments, as these controlled environments offer sterility and ways to stabilise growing conditions. Especially in this case of direct interactions, safeguarding the microbes' well-being becomes more challenging as inputs to living systems are not regulated and could potentially harm the microorganisms. In this regard, decisions regarding proximity and open habitats for direct interactions with microbes, while considered a means to foster intimate experiences [60], should be meticulously evaluated in consideration of these bio-safety aspects.

Besides maintaining a safe environment for nonhumans, designers should consider safety concerns for humans in their direct interactions with microbes. Even when dealing with non-pathogenic microbes (e.g., *C. lytica*), direct physical contact might raise concerns when encountering a large quantity of the same microorganisms, which should be further explored in designing for direct interactions with living artefacts.

The additional risk living artefacts bring due to their potential to distribute foreign living microorganisms to ecosystems is difficult to anticipate and therefore important to consider. Living artefacts designed as closed systems could in theory address this risk by collecting or destroying the microorganism after use; however, it seems prudent that all living artefacts should utilise endemic, benign, or beneficial microorganisms. Living artefacts designed using such approaches would reduce environmental impacts and might even enrich ecosystems [35, 55].

5.2.4 Sustainability and Ethics of Direct Interactions. Whether facilitating direct or indirect interactions, all living artefacts, if deployed

within existing linear models of design, production, utilisation, and waste, may pose a threat to ecosystems through the utilisation of unsustainable materials and production processes [35]. To address this, living artefacts should either use materials that can be recycled or reused within a product return system or align the diverse temporalities of materials and microbes for the safe and timely decomposition of artefacts.

The use of microorganisms within HCI raises distinct ethical concerns [3], in part because we struggle to relate to them, often resulting in ambivalence towards their welfare [41]. Organism-centred [60] and more-than-human [31, 59, 61, 87] approaches in Bio-HCI prioritise the safeguarding of microbial welfare through designing appropriate habitats and interactions centred on care practices (e.g., [33, 87]. In line with these, we call for HCI designers to give attention to microbial sensitivities in the design time, which should further encourage them to extend the nurturing of relationality and livingness beyond use time and throughout the whole life cycle of the organism. Whereas we often struggled to move further away from our human-centred approach of considering Flavobacteria as a living *medium* for HCI, there was a strong sense of what could be characterised as kinship, caregiving, and responsibility throughout the experiments conducted, as expressed below by the first author: *"I felt worried about Flavo when they were in the freeze-dryer and afterwards, to see them as a powder, in a dormant state. Therefore, I was happy to provide them access to the nutritious agar medium by pressing the super thin plastic foil. Oftentimes, I felt extremely guilty that they didn't have more space at the moment, which I hadn't really experienced before when cultivating them in a standard Petri dish. In that sense, seeing the bacteria touching the new area in the Petri dish was very satisfying. Ready to explore new territory! I would have loved to keep this interaction going, redirecting them again and again to fresh nutrients. Through the swiping experiment, at some point, some parts of the colony became less bright, which made me feel worried and guilty- had there been some left-over alcohol on the glove through which I was trying to keep them safe from other microbes? Was I exhausting them by interacting with them so frequently? Or were there simply not enough cells left at the moment to form structural colour?"*

We argue that these questions and concerns, coupled with the experience of relationality - or kinship [27], provide rich ground for further research and bode well for dynamic and reciprocal relationships with living artefacts.

5.2.5 Challenges Concerning Microbial Semantics in the Use Time. This study also revealed specific concerns related to microbial semantics [41] in direct interactions with microorganisms. For example, it might feel as though interacting with Flavobacteria by touching them through a pliable membrane is more 'disruptive' to them than leaving them to 'grow in peace' within Flavorium [23]. Therefore, even if a habitat provides Flavobacteria with their desired conditions, designers should consider to what extent the directness of interaction gives humans the idea that they contribute to microbes' wellbeing. At the same time, we need to understand better what is gained and lost from direct interactions. Even though our intention was to offer HCI designers a way to nurture human-nature connectedness through direct interactions with Flavobacteria, it is possible that direct interactions with microorganisms further cultivate feelings of disgust (e.g., [78]), resulting in a corresponding reduction in empathy. With the *FlavoToile* concept, we confront such stigma and semantic dilemmas that warrant deeper exploration in the field of HCI research concerning human-microbe interactions.

5.3 Limitations and Future Work

In this paper, we showcase three distinct studies. Among them, two involved meticulous design and prototyping of experimental setups and research artefacts tailored for Bio-HCI experiments, specifically focused on investigating direct interactions. In the *pressing* and *swiping* studies, we opted for a standard-sized Petri dish as a habitat to quickly iterate, allowing us to conduct these studies with sample triplets for more reliable results. In the *tilting* study, we employed a larger habitat because Flavobacteria's gradual response to tilt is only evident on a large spatial-scale, as initially shown by Groutars and Risseeuw et al. [23]. The experiments of the *tilting* study were therefore not conducted with sample triplets, as the larger habitats were custom-made, and this would require six (three times a control and an experimental). Even though they differentiated, all habitat sizes in the studies limited Flavobacteria's ability to expand their colonies further as well as the number of direct interactions possible within that time frame.

While the team has diverse backgrounds across HCI, design, and microbiology, providing expertise and alternative insights, it was the first author - a researcher with many years of experience working with Flavobacteria - who provided the initial interpretations of the study results. We acknowledge that the personal and long-term relationship the first author has with Flavobacteria may have caused a positive bias and awe towards the interpretation of these results. Therefore, in the future, studies with other designers and human users of living artefacts are important to explore the temporal nature of such relationalities with microbes.

Our endeavour was driven by a commitment to enrich the ongoing discourse in HCI concerning human-nature engagement and connectedness, with the goal of fostering greater comprehension and empathy towards microbes. Although we presented the technological potential for designing such engagements, we have not yet investigated whether we have successfully established the intended connections between humans and microbes over an extended period. This marks the focus of our next research endeavour. To that end, even though our explorations were oriented towards future experiments outside the lab, we acknowledge the need for additional consideration regarding the viability of the living artefacts when they are provided to human users. Moreover, a more comprehensive understanding of the interdependencies among habitat, microorganisms, and interaction variables in real-world settings is required. We know it can already be difficult for designers to understand and work with Flavobacteria's particular temporal expressions [23], and our studies add new temporal rhythms and real world variables to further complicate this. Therefore, incorporating the outcomes of these and future studies—possibly exploring additional suggested human inputs—into digital tools that support design practices with Flavobacteria (e.g., [71]) would be a valuable addition to this design space.

6 CONCLUSION

This paper delves into the notion of direct interactions with microorganisms, particularly emphasising the potential of such interactions through the lens of structurally coloured Flavobacteria. We introduce a design space that encompasses the basic habitat architecture of Flavobacteria artefacts, various input mechanisms for directly tuning their living colour, and examples of human input. Our three studies, which involve (re)activating, (re)directing, and (re)arranging Flavobacteria's colourations through pressing, tilting, and swiping, showcase the intricate interplay between human input and microbial responses. These interactions exhibit variations in proximity between humans and microorganisms and underscore the diverse response times of Flavobacteria, ranging from immediate to gradual. As well as the design space, proximity and mediation are presented as dimensions of variety to explore in direct interactions. Through our work, we seek to support the development of living artefacts that cultivate a sense of kinship and care, extending human relationality towards the microbial world and the ecosystems we all belong to.

ACKNOWLEDGMENTS

We express our gratitude to Dr. Joren Wierenga for providing practical assistance during our biolab experiments. Additionally, we extend our appreciation to Evy Murraij, our MSc graduation student, for her contributions to the project through initial activation explorations. This research received partial support from the Living Circular Labels project, funded by the Taskforce for Applied Research SIA's KIEM programme (CIE.06.007) in the Netherlands. This project was spearheaded by CARADT at Avans University of Applied Sciences in collaboration with Hoekmine B.V. and Bio4life.

REFERENCES

[1] David J. Abson, Joern Fischer, Julia Leventon, Jens Newig, Thomas Schomerus, Ulli Vilsmaier, Henrik von Wehrden, Paivi Abernethy, Christopher D. Ives, Nicolas W. Jager, and Daniel J. Lang. 2017. Leverage points for sustainability transformation. *Ambio* 46 (2 2017), 30–39. Issue 1. https://doi.org/10.1007/s13280-016-0800-y

[2] R.N. Alexander and R.T. Marshall. 1982. Moisture Loss from Agar Plates During Incubation. *Journal of Food Protection* 45 (1982), 162–163. Issue 2.

[3] Rachel Armstrong. 2022. Biodesign for a culture of life: Of microbes, ethics, and design. https://doi.org/10.21606/drs.2022.144

[4] Bahareh Barati, Elvin Karana, Sylvia Pont, and Tim van Dortmont. 2021. Living Light Interfaces - An Exploration of Bioluminescence Aesthetics. *Proceedings of the Designing Interactive Systems Conference 2021*, 1215–1229. https://doi.org/10.1145/3461778.3462038

[5] Abigail Bartlett, Daniel Padfield, Luke Lear, Richard Bendall, and Michiel Vos. 2022. A comprehensive list of bacterial pathogens infecting humans. *Microbiology (United Kingdom)* 168 (2022). Issue 12. https://doi.org/10.1099/mic.0.001269

[6] Thomas Beery, Anton Stahl Olafsson, Sandra Gentin, Megan Maurer, Sanna Stålhammar, Christian Albert, Claudia Bieling, Arjen Buijs, Nora Fagerholm, Maria Garcia-Martin, Tobias Plieninger, and Christopher M. Raymond. 2023. Disconnection from nature: Expanding our understanding of human–nature relations. *People and Nature* 5 (4 2023), 470–488. Issue 2. https://doi.org/10.1002/pan3.10451

[7] Fiona Bell, Michelle Ramsahoye, Joshua Coffie, Julia Tung, and Mirela Alistar. 2023. μMe: Exploring the Human Microbiome as an Intimate Material for Living Interfaces. *Proceedings of the 2023 ACM Designing Interactive Systems Conference*, 2019–2033. https://doi.org/10.1145/3563657.3596133

[8] Ferran Altarriba Bertran, Oğuz 'Oz Buruk, Velvet Spors, and Juho Hamari. 2023. Playful Inspiration for a New Wave of Joyful Forest Technology. *Proceedings of the 2023 ACM Designing Interactive Systems Conference*, 1886–1903. https://doi.org/10.1145/3563657.3596015

[9] Rafael A. Calvo and Dorian Peters. 2014. *Positive Computing: Technology for Wellbeing and Human Potential*. The MIT Press.

[10] Serena Camera and Elvin Karana. 2018. Experiential Characterization of Materials: toward a toolkit. https://doi.org/10.21606/drs.2018.508

[11] Michelle Chang, Chenyi Shen, Aditi Maheshwari, Andreea Danielescu, and Lining Yao. 2022. Patterns and Opportunities for the Design of Human-Plant Interaction. *DIS 2022 - Proceedings of the 2022 ACM Designing Interactive Systems Conference: Digital Wellbeing*, 925–948. https://doi.org/10.1145/3532106.3533555

[12] Louise Chawla. 2009. Growing Up Green : Becoming an Agent of Care for the Natural World. https://api.semanticscholar.org/CorpusID:53396442

[13] Dominique Chen, Young ah Seong, Hiraku Ogura, Kiichi Moriya Yuto Mitani Naoto Sekiya, Kiichi Moriya, Yuto Mi-tani, and Naoto Sekiya. 2021. Nukabot: Design of Care for Human-Microbe Relationships; Nukabot: Design of Care for Human-Microbe Relationships. *Extended Abstracts of the 2021 CHI Conference on Human Factors in Computing Systems*. https://doi.org/10.1145/3411763

[14] Adrian David Cheok, Roger Thomas Kok, Chuen Tan, Owen Noel Newton Fernando, Tim Merritt, and Janyn Yen Ping Sen. 2008. Empathetic living media. *Proceedings of the Conference on Designing Interactive Systems: Processes, Practices, Methods, and Techniques, DIS*. https://doi.org/10.1145/1394445.1394495

[15] Alessandro Chiolerio, Mohammad Mahdi Dehshibi, Diego Manfredi, and Andrew Adamatzky. 2022. Living wearables: Bacterial reactive glove. *BioSystems* 218 (8 2022). https://doi.org/10.1016/j.biosystems.2022.104691

[16] María Puig de la Bellacasa. 2010. Ethical doings in naturecultures. *Ethics, Place and Environment* 13 (2010), 151–169. Issue 2. https://doi.org/10.1080/13668791003778834

[17] Carl DiSalvo, Phoebe Sengers, and Hrönn Brynjarsdóttir. 2010. Mapping the Landscape of Sustainable HCI. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (Atlanta, Georgia, USA) *(CHI '10)*. Association for Computing Machinery, New York, NY, USA, 1975–1984. https://doi.org/10.1145/1753326.1753625

[18] Christian Dorninger, David J. Abson, Joern Fischer, and Henrik Von Wehrden. 2017. Assessing sustainable biophysical human-nature connectedness at regional scales. *Environmental Research Letters* 12 (4 2017). Issue 5. https://doi.org/10.1088/1748-9326/aa68a5

[19] Arturo Escobar. 2018. *Designs for the Pluriverse - Radical Interdependence, Autonomy, and the Making of Worlds*. Duke University Press.

[20] Robert Fletcher. 2017. Gaming conservation: Nature 2.0 confronts nature-deficit disorder. *Geoforum* 79 (2 2017), 153–162. https://doi.org/10.1016/j.geoforum.2016.02.009

[21] William Gaver, Andy Boucher, Michail Vanis, Andy Sheen, Dean Brown, Liliana Ovalle, Naho Matsuda, Amina Abbas-Nazari, and Robert Phillips. 2019. My naturewatch camera disseminating practice research with a cheap and easy DIY design. *Conference on Human Factors in Computing Systems - Proceedings*. https://doi.org/10.1145/3290605.3300532

[22] William W Gaver, John Bowers, Andrew Boucher, Hans Gellerson, Sarah Pennington, Albrecht Schmidt, Anthony Steed, Nicholas Villars, and Brendan Walker. 2004. The Drift Table: Designing for Ludic Engagement. , 16 pages. https://doi.org/10.1145/985921.985947

[23] Eduard Georges Groutars, Carmen Clarice Risseeuw, Colin Ingham, Raditijo Hamidjaja, Willemijn S. Elkhuizen, Sylvia C. Pont, and Elvin Karana. 2022. Flavorium: An Exploration of Flavobacteria's Living Aesthetics for Living Color Interfaces. *Conference on Human Factors in Computing Systems - Proceedings*. https://doi.org/10.1145/3491102.3517713

[24] Foad Hamidi and Melanie Baljko. 2014. Rafigh: A living media interface for speech intervention. *Conference on Human Factors in Computing Systems - Proceedings*, 1817–1820. https://doi.org/10.1145/2556288.2557402

[25] Raditijo Hamidjaja, Jérémie Capoulade, Laura Catón, and Colin J. Ingham. 2020. The cell organization underlying structural colour is involved in Flavobacterium IR1 predation. *ISME Journal* 14 (11 2020), 2890–2900. Issue 11. https://doi.org/10.1038/s41396-020-00760-6

[26] Donna J. Haraway. 2003. The Companion Species Manifesto: Dogs, People, and Significant Otherness.

[27] Donna J. Haraway. 2016. *Staying with the Trouble: Making Kin in the Chthulucene*. Duke University Press.

[28] Terry Hartig, Agnes E. Van Den Berg, Caroline M. Hagerhall, Marek Tomalak, Nicole Bauer, Ralf Hansmann, Ann Ojala, Efi Syngollitou, Giuseppe Carrus, Ann Van Herzele, Simon Bell, Marie Therese Camilleri Podesta, and Grete Waaseth. 2011. *Health benefits of nature experience: Psychological, social and cultural processes*. Springer Netherlands. 127–168 pages. https://doi.org/10.1007/978-90-481-9806-1_5

[29] Dominique Hes and Chrisna du Plessis. 2014. *Designing for Hope - Pathways to Regenerative Sustainability*. Routledge.

[30] Andrew J. Howell, Raelyne L. Dopko, Holli Anne Passmore, and Karen Buro. 2011. Nature connectedness: Associations with well-being and mindfulness. *Personality and Individual Differences* 51 (7 2011), 166–171. Issue 2. https://doi.org/10.1016/j.paid.2011.03.037

[31] Yuta Ikeya, Ron Wakkary, and Bahareh Barati. 2023. Metamorphonic: A Reflective Design Inquiry into Human-Silkworm Relationship. *Proceedings of the 2023 ACM Designing Interactive Systems Conference*, 808–819. https://doi.org/10.1145/3563657.3596053

[32] Villads Egede Johansen, Laura Catón, Raditijo Hamidjaja, Els Oosterink, Bodo D. Wilts, Torben Sølbeck Rasmussen, Michael Mario Sherlock, Colin J. Ingham,

and Silvia Vignolini. 2018. Genetic manipulation of structural color in bacterial colonies. *Proceedings of the National Academy of Sciences of the United States of America* 115 (2018). Issue 11. https://doi.org/10.1073/pnas.1716214115

[33] Elvin Karana, Bahareh Barati, and Elisa Giaccardi. 2020. Living artefacts: Conceptualizing livingness as a material quality in everyday artefacts. *International Journal of Design* 14 (2020). Issue 3.

[34] Elvin Karana, Bahareh Barati, Valentina Rognoli, and Anouk Zeeuw van der Laan. 2015. Material driven design (MDD): A method to design for material experiences. *International Journal of Design* 9 (2015). Issue 2.

[35] Elvin Karana, Holly McQuillan, Valentina Rognoli, and Elisa Giaccardi. 2023. Living artefacts for regenerative ecologies. *Research Directions: Biotechnology Design* 1 (2023). https://doi.org/10.1017/btd.2023.10

[36] Keune. 2022. Between breakfast and bed: Towards fluid modes of designing and cohabiting with living organisms. (2022). https://doi.org/10

[37] Betty Kientz, Hélène Agogué, Céline Lavergne, Pauline Marié, and Eric Rosenfeld. 2013. Isolation and distribution of iridescent Cellulophaga and other iridescent marine bacteria from the Charente-Maritime coast, French Atlantic. *Systematic and Applied Microbiology* 36 (6 2013), 244–251. Issue 4. https://doi.org/10.1016/j.syapm.2013.02.004

[38] Betty Kientz, Stephen Luke, Peter Vukusic, Renaud Péteri, Cyrille Beaudry, Tristan Renault, David Simon, Tâm Mignot, and Eric Rosenfeld. 2016. A unique self-organization of bacterial sub-communities creates iridescence in Cellulophaga lytica colony biofilms. *Scientific Reports* 6 (2016). https://doi.org/10.1038/srep19906

[39] Betty Kientz, Pauline Marié, and Eric Rosenfeld. 2012. Effect of abiotic factors on the unique glitter-like iridescence of Cellulophaga lytica. *FEMS Microbiology Letters* 333 (2012). Issue 2. https://doi.org/10.1111/j.1574-6968.2012.02614.x

[40] Raphael Kim, Pat Pataranutaporn, Jack Forman, Seung Ah Lee, Ingmar H. Riedel-Kruse, Mirela Alistar, Eldy S. Lazaro Vasquez, Katia Vega, Roland Van Dierendonck, Gilad Gome, Oren Zuckerman, Angela Vujic, David S. Kong, Pattie Maes, Hiroshi Ishii, Misha Sra, and Stefan Poslad. 2021. Microbe-HCI: Introduction and Directions for Growth. *Extended Abstracts of the 2021 CHI Conference on Human Factors in Computing Systems*, 1–4. https://doi.org/10.1145/3411763.3450408

[41] Raphael Kim, Clarice Risseeuw, Eduard Georges Groutars, and Elvin Karana. 2023. Surfacing Livingness in Microbial Displays: A Design Taxonomy for HCI. *Conference on Human Factors in Computing Systems - Proceedings*. https://doi.org/10.1145/3544548.3581417

[42] Raphael Kim, Siobhan Thomas, Roland Van Dierendonck, and Stefan Poslad. 2018. A new mould rush: Designing for a slow bio-digital game driven by living micro-organisms. *ACM International Conference Proceeding Series*. https://doi.org/10.1145/3235765.3235798

[43] Amy T. Lam, Joyce Ma, Cory Barr, Seung Ah Lee, Adam K. White, Kristina Yu, and Ingmar H. Riedel-Kruse. 2019. First-hand, immersive full-body experiences with living cells through interactive museum exhibits. *Nature Biotechnology* 37 (10 2019), 1238–1241. Issue 10. https://doi.org/10.1038/s41587-019-0272-2

[44] Kyungwon Lee, Jaewoo Jung, and Seung Ah Lee. 2020. MicroAquarium: An immersive and interactive installation with living microorganisms. *Conference on Human Factors in Computing Systems - Proceedings*. https://doi.org/10.1145/3334480.3383164

[45] Seung Ah Lee, Engin Bumbacher, Alice M. Chung, Nate Cira, Byron Walker, Ji Young Park, Barry Starr, Paulo Blikstein, and Ingmar H. Riedel-Kruse. 2015. Trap it! : A playful human-biology interaction for a museum installation. *Proceedings of the 2015 CHI Conference on Human Factors in Computing Systems* 2015-April, 2593–2602. https://doi.org/10.1145/2702123.2702220

[46] Chenghai Li, Qiguang He, Yang Wang, Zhijian Wang, Zijun Wang, Raja Annapooranan, Michael I. Latz, and Shengqiang Cai. 2022. Highly robust and soft biohybrid mechanoluminescence for optical signaling and illumination. *Nature Communications* 13 (12 2022), 3914. Issue 1. https://doi.org/10.1038/s41467-022-31705-6

[47] Qing Li. 2010. Effect of forest bathing trips on human immune function. *Environmental Health and Preventive Medicine* 15 (1 2010), 9–17. Issue 1. https://doi.org/10.1007/s12199-008-0068-3

[48] Ann Light, Irina Shklovski, and Alison Powell. 2017. Design for existential crisis. *Conference on Human Factors in Computing Systems - Proceedings* Part F127655, 722–733. https://doi.org/10.1145/3027063.3052760

[49] Living Light. 2023. Living Light Home Page. https://livinglight.info/

[50] Youn Kyung Lim, Erik Stolterman, Heekyoung Jung, and Justin Donaldson. 2007. Interaction gestalt and the design of aesthetic interactions. *Proceedings of the 2007 Conference on Designing Pleasurable Products and Interfaces, DPPI'07*, 239–254. https://doi.org/10.1145/1314161.1314183

[51] Jen Liu, Daragh Byrne, and Laura Devendorf. 2018. Design for collaborative survival: An inquiry into human-fungi relationships. *Conference on Human Factors in Computing Systems - Proceedings* 2018-April. https://doi.org/10.1145/3173574.3173614

[52] Szu Yu Liu, Shaowen Bardzell, and Jeffrey Bardzell. 2019. Symbiotic encounters: HCI and sustainable agriculture. *Conference on Human Factors in Computing Systems - Proceedings*. https://doi.org/10.1145/3290605.3300547

[53] Xinyue Liu, Hyunwoo Yuk, Shaoting Lin, German Alberto Parada, Tzu Chieh Tang, Eléonore Tham, Cesar de la Fuente-Nunez, Timothy K. Lu, and Xuanhe Zhao. 2018. 3D Printing of Living Responsive Materials and Devices. *Advanced Materials* 30 (1 2018). Issue 4. https://doi.org/10.1002/adma.201704821

[54] Dan Lockton, Delanie Ricketts, Shruti Aditya Chowdhury, and Chang Hee Lee. 2017. Exploring qualitative displays and interfaces. *Conference on Human Factors in Computing Systems - Proceedings* Part F127655, 1844–1852. https://doi.org/10.1145/3027063.3053165

[55] LoopBiotech. 2023. Loop Biotech. https://loop-biotech.com/nl/

[56] Richard Louv. 2013. *Last Child in the Woods: Saving our Children from Nature-Deficit Disorder*. Atlantic Books.

[57] Michael T. Madigan, Kelly S. Bender, Daniel H. Buckley, W. Matthew Sattley, David A. Stahl, and Thomas Dale Brock. 2022. *Brock Biology of Microorganisms*. Pearson.

[58] Timothy Merritt, Foad Hamidi, Mirela Alistar, and Marta DeMenezes. 2020. Living media interfaces: a multi-perspective analysis of biological materials for interaction. *Digital Creativity* 31 (1 2020), 1–21. Issue 1. https://doi.org/10.1080/14626268.2019.1707231

[59] Netta Ofer and Mirela Alistar. 2023. Felt Experiences with Kombucha Scoby: Exploring First-person Perspectives with Living Matter. *Conference on Human Factors in Computing Systems - Proceedings*. https://doi.org/10.1145/3544548.3581276

[60] Netta Ofer, Fiona Bell, and Mirela Alistar. 2021. Designing Direct Interactions with Bioluminescent Algae. *DIS 2021 - Proceedings of the 2021 ACM Designing Interactive Systems Conference: Nowhere and Everywhere*, 1230–1242. https://doi.org/10.1145/3461778.3462090

[61] Gizem Oktay, Yuta Ikeya, Minha Lee, Bahareh Barati, Youngsil Lee, Yuning Chen, Larissa Pschetz, and Carolina Ramirez-Figueroa. 2023. Designing with the more-than-human: Temporalities of thinking with care. *DIS 2023 Companion: Companion Publication of the 2023 ACM Designing Interactive Systems Conference*, 104–106. https://doi.org/10.1145/3563703.3591462

[62] David W. Orr. 1992. *Ecological literacy: Education and transition to a post modern world*. State University of New York Press.

[63] Bum Jin Park, Yuko Tsunetsugu, Tamami Kasetani, Takahide Kagawa, and Yoshifumi Miyazaki. 2010. The physiological effects of Shinrin-yoku (taking in the forest atmosphere or forest bathing): Evidence from field experiments in 24 forests across Japan. *Environmental Health and Preventive Medicine* 15 (1 2010), 18–26. Issue 1. https://doi.org/10.1007/s12199-009-0086-9

[64] Tytti Pasanen. 2019. Everyday Physical Activity in Natural Settings and Subjective Well-Being Direct Connections and Psychological Mediators.

[65] Pat Pataranutaporn, Todd Ingalls, and Ed Finn. 2018. Biological HCI: Towards integrative interfaces between people, computer, and biological materials. *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems* 2018-April, 1–6. https://doi.org/10.1145/3170427.3188662

[66] Pat Pataranutaporn, Angela Vujic, David S. Kong, Pattie Maes, and Misha Sra. 2020. Living Bits: Opportunities and Challenges for Integrating Living Microorganisms in Human-Computer Interaction. *ACM International Conference Proceeding Series*. https://doi.org/10.1145/3384657.3384783

[67] Amrita Pati, Birte Abt, Hazuki Teshima, Matt Nolan, Alla Lapidus, Susan Lucas, Nancy Hammon, Shweta Deshpande, Jan Fang Cheng, Roxane Tapia, Cliff Han, Lynne Goodwin, Sam Pitluck, Konstantinos Liolios, Ioanna Pagani, Konstantinos Mavromatis, Galina Ovchinikova, Amy Chen, Krishna Palaniappan, Miriam Land, Loren Hauser, Cynthia D. Jeffries, John C. Detter, Evelyne Marie Brambilla, K. Palani Kannan, Man fred Rohde, Stefan Spring, Markus Göker, Tanja Woyke, James Bristow, Jonathan A. Ei-Sen, Victor Markowitz, Philip Hugenholtz, Nikos C. Kyrpides, Hans Peter Klenk, and Natalia Ivanova. 2011. Complete genome sequence of Cellulophaga lytica type strain (LIM-21 T). *Standards in Genomic Sciences* 4 (2011), 221–232. Issue 2. https://doi.org/10.4056/sigs.1774329

[68] James Pierce, Yolande Strengers, Phoebe Sengers, and Susanne Bødker. 2013. Introduction to the special issue on practice-oriented approaches to sustainable HCI. *ACM Transactions on Computer-Human Interaction* 20 (2013). Issue 4. https://doi.org/10.1145/2494260

[69] Majken K. Rasmussen, Esben W. Pedersen, Marianne G. Petersen, and Kasper Hornbæk. 2012. Shape-changing interfaces: A review of the design space and open research questions. *Conference on Human Factors in Computing Systems - Proceedings*. https://doi.org/10.1145/2207676.2207781

[70] Ingmar H. Riedel-Kruse, Alice M. Chung, Burak Dura, Andrea L. Hamilton, and Byung C. Lee. 2011. Design, engineering and utility of biotic games. *Lab on a Chip* 11 (1 2011), 14–22. https://doi.org/10.1039/c0lc00399a

[71] Clarice Risseeuw, Jose Francisco Martinez Castro, Pascal Barla, and Elvin Karana. 2023. FlavoMetrics: Towards a Digital Tool to Understand and Tune Living Aesthetics of Flavobacteria. *Proceedings of the 2023 ACM Designing Interactive Systems Conference*, 2079–2092. https://doi.org/10.1145/3563657.3596085

[72] Shannon Rodgers, Kellie Vella, Bernd Ploderer, and Margot Brereton. 2023. Nature Fictions: Designing for a Sustainable Future through Nature Relations. *Proceedings of the 2023 ACM Designing Interactive Systems Conference*, 1566–1580. https://doi.org/10.1145/3563657.3595981

[73] Lukas Schertel, Gea T. van de Kerkhof, Gianni Jacucci, Laura Catón, Yu Ogawa, Bodo D. Wilts, Colin J. Ingham, Silvia Vignolini, and Villads E. Johansen. 2020.

Complex photonic response reveals three-dimensional self-organization of structural coloured bacterial colonies. *Journal of the Royal Society Interface* 17 (5 2020). Issue 166. https://doi.org/10.1098/rsif.2020.0196

[74] Aybars Senyildiz. 2022. Why would I ever fry and eat my SCOBY? It would be like murder! Attuning to nonhumans through kombucha fermentation practices. https://doi.org/10.21606/drs.2022.318

[75] Nancy Smith, Shaowen Bardzell, and Jeffrey Bardzell. 2017. Designing for cohabitation: Naturecultures, hybrids, and decentering the human in design. *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems* 2017-May, 1714–1725. https://doi.org/10.1145/3025453.3025948

[76] Masashi Soga and Kevin J. Gaston. 2015. Extinction of experience: the loss of human-nature interactions. http://hdl.handle.net/10871/18516

[77] Claretta J. Sullivan, Kennedy Brown, Chia Suei Hung, Joseph Kuo Hsiang Tang, Mark DeSimone, Vincent Chen, Pamela F. Lloyd, Maneesh Gupta, Abby Juhl, Wendy Crookes-Goodson, Milana Vasudev, Patrick B. Dennis, and Nancy Kelley-Loughnane. 2023. Iridescent biofilms of Cellulophaga lytica are tunable platforms for scalable, ordered materials. *Scientific reports* 13 (12 2023), 13192. Issue 1. https://doi.org/10.1038/s41598-023-38797-0

[78] A. Toomey. 2010. Visible Invisibility: Contamination Aware Textile Surfaces. , 357-367 pages. https://doi.org/10.1533/9780857090348.357

[79] Minh Xuan A. Truong and Susan Clayton. 2020. *Technologically transformed experiences of nature: A challenge for environmental conservation?* Ph. D. Dissertation. https://doi.org/10.1016/j.biocon.2020.108532

[80] Anna Lowenhaupt Tsing. 2021. *The Mushroom at the End of the World: On the Possibility of Life in Capitalist Ruins*. Princeton University Press.

[81] Anna Lowenhaupt Tsing, Heather Anne Swanson, Elaine Gan, and Nils Bubandt. 2017. *Arts of Living on a Damaged Planet Ghosts and Monsters of the Anthropocene*. University of Minnesota Press.

[82] Will R Turner, Toshihiko Nakamura, and Marco Dinetti. 2004. Global Urbanization and the Separation of Humans from Nature. Issue 6. https://academic.oup.com/bioscience/article/54/6/585/294707

[83] Gea T. van de Kerkhof, Lukas Schertel, Laura Catòn, Thomas G. Parton, Karin H. Müller, Heather F. Greer, Colin J. Ingham, and Silvia Vignolini. 2022. Polysaccharide metabolism regulates structural colour in bacterial colonies. *Journal of The Royal Society Interface* 19 (5 2022). Issue 190. https://doi.org/10.1098/rsif.2022.0181

[84] Sarah Webber, Ryan M. Kelly, Greg Wadley, and Wally Smith. 2023. Engaging with Nature through Technology: A Scoping Review of HCI Research. *Conference on Human Factors in Computing Systems - Proceedings*. https://doi.org/10.1145/3544548.3581534

[85] Edward O. Wilson. 1984. *Biophilia*. Harvard University Press.

[86] Jiwei Zhou, Bahareh Barati, Elisa Giaccardi, and Elvin Karana. 2022. Habitabilities of Living Artefacts: A Taxonomy of Digital Tools for Biodesign. *International Journal of Design* 16 (2022), 57–73. Issue 2. https://doi.org/10.57698/v16i2.05

[87] Jiwei Zhou, Raphael Kim, Zjenja Doubrovski, Joana Martins, Elisa Giaccardi, and Elvin Karana. 2023. Cyano-chromic Interface: Aligning Human-Microbe Temporalities Towards Noticing and Attending to Living Artefacts. *Proceedings of the 2023 ACM Designing Interactive Systems Conference*, 820–838. https://doi.org/10.1145/3563657.3596132