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DOI
10.1145/3544548.3581417

Publication date
2023

Document Version
Final published version

Published in
CHI '23: Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems

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A Design Taxonomy for HCI

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ABSTRACT

In recent years, there has been a notable proliferation and diversification of works in HCI, that integrate living microorganisms; an imperative lifeform dominating ecosystems of our planet. Yet despite the growing interest, there is a lack of structured lenses with which designers can strategize their processes of surfacing livingness; a material quality inherent in living artefacts with a potential to enrich user experiences and to initiate mutualistic care between humans and microorganisms. Through a systematic artefacts review and a case study on Flavobacteria, we have developed and instantiated a Taxonomy of Surfacing Livingness in Microbial Displays, consisting of six microbe-sensitive, tuneable mechanisms for human noticing of microorganisms: 1) Canvassing, 2) Marking, 3) Magnifying, 4) Translating, 5) Nudging, and 6) Molecular Programming. The taxonomy invites diverse and adaptable ways of generating and crafting microbial displays; towards overcoming microbe-specific surfacing constraints, integrating diverse stakeholders' values, and enabling nuanced address of microbial welfare.

CCS CONCEPTS

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

KEYWORDS

Microbes, livingness, living aesthetics, biological-HCI, biodesign, taxonomy

ACM Reference Format:
Raphael Kim, Clarice Risseeuw, Eduard Groutars, and Elvin Karana. 2023. Surfacing Livingness in Microbial Displays: A Design Taxonomy for HCI. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems (CHI '23), April 23–28, 2023, Hamburg, Germany*. ACM, New York, NY, USA, 21 pages. https://doi.org/10.1145/3544548.3581417

CHI '23, April 23–28, 2023, Hamburg, Germany

ACM ISBN 978-1-4503-9421-5/23/04.
https://doi.org/10.1145/3544548.3581417

1 INTRODUCTION

Described as any organisms that are (usually) too small to be seen with naked human eye, *microbes* are one of the most abundant, diverse, and earliest life forms on Earth [106]. Microbes play an intrinsic role in almost every natural cycle, supporting existence of all higher trophic lifeforms, and the health of the global climate [19]. For us humans, just one of many co-habitants existing on the planet, our microbial companion species [52, 53] have also been, and will continue to, profoundly shape the ways with which humans interact and experience the world. Our growing understanding of this significance further drives the ongoing microbial imperative for us to better *notice*, to respond to, and to care for, the so-called invisible majority; through various means of observations, discussions, and learning [106, 107, 125].

In HCI, microbial significance has also been recognized. Whilst gathering of a special interest group, *microbe-HCI*, at CHI 2021 [71] has been a recent and a fitting hommage, microbial explorations in HCI and interaction design stretch back for more than 20 years (e.g., [36]), with a notable increase and diversification of works in the last 10 years. And yet, despite the ongoing and a growing interest, there is currently a lack of an overarching, systemic set of microbe-sensitive design tools in HCI, that could help designers to strategize and to explore how microbes could be better displayed, noticed, and experienced as living media.

As biodesign practitioners with professional background and experiences of implementing microbiology, we acknowledge that designing microbial displays can pose many challenges, owing to the distinct blend of material qualities inherent in microbial species; most famously for their size, but also in their temporal and semantic idiosyncrasies. With the ever growing awareness of microbial imperatives and encounters in our everyday lives, time has now come, for us to be more attentive towards the art of surfacing the microbial world.

In response, we have developed a *Taxonomy of Surfacing Livingness in Microbial Displays*, a portfolio of adaptable design lenses (and mechanisms) to help prospective designers with their microbial explorations in HCI. Specifically, the taxonomy helps designers to strategize how livingness of microbes could be made more noticeable to the human senses, the process which we refer to as surfacing. Defined as *"the condition or the quality of having life and being alive"* [23], *livingness* is a fundamental material quality that should be made noticeable in microbial *living artefacts* [64]. On a functional level, surfacing microbial livingness simply enables users of living artefacts to notice the status of its operation. However, as existing research shows, surfacing livingness can also offer experiential opportunities for users too, helping to bring a sense of shared vitality [98], promote user engagement with living artefacts (e.g., [59, 74, 87]), and increase levels of empathy and care in people (e.g., [20, 21, 48]).

Developed over a six-month period through a systematic microbial living artefact collection and collaborative analysis, the taxonomy consists of six mechanisms with which microbial livingness can be surfaced and displayed in living artefacts: 1) Canvassing, 2) Marking, 3) Magnifying, 4) Translating, 5) Nudging, and 6) Molecular Programming. We have instantiated the taxonomy through a case study, which discuss ways with which each mechanism could be tuned and combined to address various challenges and to integrate values across HCI communities.

We situate our work at the intersection of biological-HCI [113] and post-anthropocentric HCI (e.g., [28]), to make the following contributions. First, the taxonomy offers a range of surfacing mechanisms, which can also be layered together in various combinations to address surfacing challenges in producing microbial displays. It offers customizability to help with the tuning [65] and refinement of microbial displays in addressing the technical, experiential, and ethical challenges endemic in microbe-to-human communication. Second, the taxonomy offers a non-anthropocentric approach towards working with microbes. Specifically, these mechanisms are ordered according to increasing levels of human intervention and technical control over microbe's integrity, thus helping designers to become better aware of possible alternatives and ethical considerations, and enabling them to make informed choices in their processes. Third, through systematic artefact review and analysis, we highlight design patterns commonly observed in HCI, and those that are under-explored, presenting fresh avenues for research and multidisciplinary collaboration. And more broadly, we invite designers to consider re-imagining, re-evaluating, and re-configuring our understanding of human-technology-microbe relationships.

2 MICROBIAL SURFACING CONSTRAINTS

In Table 1, we outline microbe-specific surfacing "constraints", that arise from the organisms' distinct material qualities. These constraints could hinder humans in noticing of microbes' livingness, and may in turn require microbe-appropriate design strategies for the livingness to be adequately and appropriately brought forward to our human senses.

2.1 Technical Constraints

Microscopic size of most species means that humans are often unable to visually detect the physical presence, as well as their temporality of livingness. Microbial growth, movement, and gene expressions for example, may appear invisible and/or perceived to be "too slow" to the naked human eye without relying on other senses (e.g., smell) and/or application of appropriate technical facilitation (e.g., microscopy). In addition, some microbial species have translucent bodies (e.g., [130]), which necessitates technical assistance (e.g., through custom light setup) for adequate visualization.

2.2 Practical Constraints

Currently, only less than 1% of microbes on Earth can be isolated and cultivated [33], due to complex environmental requirements of most microbial species. This may pose practical challenges in how certain microbes could be displayed. Designers may need to work in open environments and with other surrounding species in order to produce their artefacts. As such, the quality of displays could be compromised given the openness of the environment and lack of control in how the displays are produced. And lastly, some microbes are pathogenic and potentially unsafe for designers to handle. Extra provision and special access may be necessary to produce displays of pathogenic microbial species.

2.3 Semantic Constraints

For livingness of plants and trees, their meanings can be relatively easily recognized (and also interpreted) by humans (e.g., [57], p.215; [115], p.4). For microbes, this may not be so straightforward. They are often amorphous (lacking cell differentiation), which could create visual ambiguity as a display. Microbes' appearances may seem indifferent to other non-living materials: Mycelium could be mistaken for a bundle of cotton, glowing bacteria as LEDs (e.g., [72]), and the so-called "dog vomit slime mould" [61] as a real dog vomit(!). Without context and added visual cues to surface their livingness, microbes may thus prove challenging semantically, for humans to notice. These highlight a microbe-sensitive design space that would technically and/or artistically address the visual ambiguity, towards enhancing their recognizability.

In addition, in most human societies, there is a general negative perception around microbes (e.g., [15, 34]). For instance, humans often feel disgust at the sight of mouldy bread, mildews on bathroom tiles, dental plaques on people's mouths, etc. And as such, observing certain species of microbes (e.g., moulds) may create negatively-biased experiences. This can be potentially problematic for certain artefacts, as the success of the design may for instance depend on people feeling empathetic towards the integrated microbes. In this case, direct visualization of microbes may be inappropriate, requiring alternative strategies (e.g., [3], p.11-12).

As these features highlight, designing with microbes can be challenging from multi-variant perspectives (practical, technical, and semantic), in enabling humans to adequately and appropriately notice their livingness. And given the significant roles that microbes play in our lives and in sustaining our ecosystems, these constraints ought to pose deeper concerns to biodesigners. They certainly have further strengthened our motivation behind developing better ways, to surface microbial livingness; an important sign and a starting point for humans to proactively interact, experience, and collaborate with our imperative microbial companions.

3 RELATED WORKS

3.1 Biological-HCI

Defined as a design framework (and also an emerging community in HCI) that *"investigates the relationship between human, computer, and biological systems by redefining biological materials as design elements"* ([113], p.1), biological-HCI (or "bio-HCI") has been helping researchers to better articulate and position living material

Table 1: Microbe-Specific Surfacing Constraints

Category	Type	Material Quality	Surfacing Constraint	References
Technical	Size	Microscopic in size	Too small	(e.g., [130])
Technical	Opacity	Translucent bodies	Too transparent	(e.g., [130])
Technical	Temporality	Slow response time	Too slow	(e.g., [101])
Practical	Culturability	Unculturable	Cannot be displayed alone	(e.g., [33])
Practical	Pathogenicity	Pathogenic	Inaccessible	(e.g., [31])
Semantic	Morphology	Amorphous	Visual ambiguity	(e.g., [110])
Semantic	Composition	Representation through host	Hidden identity	(e.g., [17])
Semantic	Reputability	Negative bias	Experiential bias	(e.g., [3])

explorations under the language and communities of design. Similarly, recently introduced concepts such as *Living Bits* [114], and *Living Media Interfaces* [96], have brought forward the notion of living organisms as novel forms of computers and interfaces, thus introducing a much-needed and a timely set of vocabularies for researchers operating at the intersection of biology, computer science, and design. Taking inspiration from these developments in HCI, our work aims to add further nuances to the emergent conversations, by continuing to recognize and to attend to the diverse values of interaction agents across the kingdoms of life; focusing specifically on microbes and their relationship regarding humans and technology.

In terms of *microbial* explorations in HCI, a variety of microbial genus and species, representing different types of fungi, yeasts, bacteria, and protists, etc., in both living and non-living forms, have been investigated. Such works have come in the forms of: workshops (e.g., [43, 44]); theories/frameworks (e.g., [40, 54, 70, 72, 96, 113, 114]); reviews (e.g., [45, 86, 111, 134]); critical/speculative designs (e.g., [32, 124]); educational tools (e.g., [24, 35, 41, 42, 48, 58, 59, 82]); sensors (e.g., [20, 78]); self-trackers (e.g., [10, 21]); material/system characterisations (e.g., [1, 6–8, 46, 105, 129]); biofabrications (e.g., [14, 15, 83, 104, 108, 127]; artworks (e.g., [2, 4, 50, 77, 84, 123]); wearables (e.g., [38, 89, 93, 102, 103, 128, 131]); robotics (e.g., [55, 56, 112]); games (e.g., [68, 75, 79, 81, 116]); and interactive public installations (e.g., [39, 80, 85, 87]), to name a consortium of examples.

In short, microbial explorations in biological-HCI (i.e., microbe-HCI) have been, and will likely to continue to proliferate and diversify, embodying diverse design goals, values, and ways of imagining.

3.2 Surfacing Livingness in HCI

In interaction design, displaying livingness in various non-human agents, including plants and animals, is regarded as a useful design strategy. Research in human-plant interaction (HPI) studies for example, have suggested that showing growth and movement in plant-based interfaces, can enhance levels of user engagement, empathy, and behavioural change (e.g., [27, 57, 121]). In contrast, livingness of animals, surfaced through their behavioural patterns (e.g., tail wagging in dogs [118]), are often used in animal computer interaction (ACI) studies, as a guide to help researchers to better attend to the animals' welfare (e.g., [16, 109, 118]).

In essence, surfacing livingness of non-human agents in interaction design, is a compelling way to generate experiences that are engaging, meaningful, and empathetic, addressing the values of both the human and the non-human stakeholders in the process.

In biological-HCI too, a display of livingness of microorganisms is also regarded as a desirable design element, when living artefacts are examined in terms of their function and experiential qualities. The display indicates an operational state of living artefacts [64], whilst offering experiential potentials too, such as increased user engagement and empathy (e.g., [20, 21, 48, 59, 74, 87]). Various forms of microbiological phenomena that drive livingness has been explored in HCI, ranging from growth (e.g., [46, 48, 75]), bioluminescence (e.g., [6, 105]), movements (e.g., [59, 79, 87]), fermentation (e.g., [20, 50]), and transgene expressions (e.g., [2, 21, 50]).

3.2.1 Existing Guidelines on Surfacing Livingness of Microbes. We unpack some of the existing theoretical contributions in HCI, evaluating published guidelines on how they have so far helped designers to craft possible ways with which microorganisms' livingness could be surfaced via displays. We then base the insights to elucidate potential values of our work in helping to further support designers in interaction design and HCI. In Gerber et al.'s *"design rules for integrating biological matter into digital games"* [40], the authors outlined seven practical rules for the enhancement of playful human-biology interactions. These included, for instance, the rule (number two) of matching of human and microbiological length and time scales, by means of calibration of magnification levels under which microbes' movements are observed (ibid., p.9-10). The rule (number three) of using digital graphic overlays to help users to track unpredictable movements of microorganisms (ibid., p.10-11); is another rule from the paper that had been applied by designers towards temporal tuning of microbial responses to external stimuli (e.g., [39, 68, 85]).

On a more *bio*-technical level, in discussing *Empathetic Living Media* [21], its authors have identified DNA alteration (of organisms) as one of the major dimensions to consider when designing with living materials (ibid., p.471-472). Through demonstration of an artefact involving genetically modified *E.coli*, programmed to glow with intensity levels corresponding to health-related information of a person; the work argued for the value of DNA alteration, in diversifying ways with which living displays could help people to become more empathetic with their own personal (health) data. Additionally, other recommendations have included implementation of Internet of Things (IoT) infrastructure to prolong user engagement (e.g., [59, 74]), and the application of electron flow sensing technologies to aid observation of micro-fluctuations in microbial metabolism in real time (e.g., ([3], p.11-12); [122]).

These guidelines and examples will likely to continue in their support of future interactive biodesigns that aim to facilitate seamless surfacing of microbial livingness. However, we also note the preliminary nature of these works, to suggest that further extensions may provide designers with a more systemic vantage point. In particular, there has been a recent growth in HCI works that explore microbes from a non-anthropocentric viewpoint, which warrant a different type of mechanism to display livingness of microbes. In the following, we explain what such mechanisms are, and why they are important to be included as part of our proposed taxonomy.

3.3 Microbial Displays for Care in HCI

A growing number of HCI researchers and designers are beginning to challenge the traditional notions of what microbes are in HCI; exploring less function-driven, and more sensitive ways to design with the organisms. Echoing the concepts of human de-centring and designing for multi-species – as previously addressed within Animal Computer Interaction [95] and Human Plant Interaction [5] – they see microorganisms as "collaborators" (e.g., [89], p.2; [3]), whose welfare should be considered as part of designing for mutualistic care ([64], p.46) and symbiotic encounters [90] between the human and the non-human stakeholders. Similarly, Ofer et al.'s organism centred approach [105] is a design framework that embodies the non-anthropocentric philosophy. By proposing that optimization of microbes' environmental conditions should take priority before further design decisions can be made, the framework challenges the traditional notions of human-centred designs that often put human needs at the top of the agenda.

Consequently, existing related works in this area have demonstrated that microbial displays should integrate values of both the human as well as the non-human in their design. They argue that microbial displays need to do more; beyond merely projecting livingness of microorganisms for the sake of human detection, and towards emotive communication of microbial welfare. Through exploring designerly ways of conveying microbes' state of wellbeing (e.g., thriving or struggling), and of enticing or encouraging its human observers to take appropriate (care) actions for the microbes; they have begun to push the boundaries of conventional display requirements, from anthropocentric adequacy to non-anthropocentric appropriateness. For example, these explorations are most evident in *Nukabot* [20], an interactive maturation cask that facilitates human-microbe collaborations of fermentation. Here, display of microbial livingness was essential, as it influenced the quality of the outcomes of the collaboration (i.e., vitality of microbes and pickled vegetables). Furthermore, the display had to communicate to the human collaborator on an emotional level, to ensure that *Nukabot*'s lactic acid bacteria were well looked after.

To overcome these semantic challenges, designers deployed multiple layers of technical and cultural tools to carefully translate and craft how the microbes were displayed. These included use of culturally familiar display elements imbued with traditional *yōkai* and *tsukumogami* aesthetics, and an anthropomorphic style of display. Such work demonstrates the advantages of technical translations towards overcoming potential semantic challenges posed by microorganisms' aesthetics. In response, our proposed taxonomy allows for technically translated explorations, as well as a non-anthropocentric approach. In essence, the taxonomy strives to empower designers with a broader choice and awareness, to ensure that non-human (e.g., microbial) values can be strategically baked into their design outcomes.

4 METHODOLOGY

4.1 Systematic Living Artefact Collection

To begin the process of taxonomy development, a systematic artefact collection was undertaken, to identify living artefacts involving microorganisms, across HCI and design venues. This was to gain a better understanding of how designers have displayed microorganisms in the living artefacts, in particular the ways of showing how microbes' living qualities change over time through growth, colour change, movement, and so forth. We then broke the displays down into designable (and tuneable) mechanisms, which were categorized and ordered into a taxonomy. Three databases were searched: ACM Digital Library, IEEE, and SpringerLink. The living artefacts collection was completed in four phases: identification, screening, eligibility, and supplementation (Fig. 1). Searches were limited to works created from year 2008 onward, to mark one of the earliest notable living artefacts for human-microbe interaction, Cheok et al.'s *Empathetic Living Media* [21].

4.1.1 Phase 1: Literature Gathering. This was undertaken within a two-week period in February 2022. Table 2 lists the search strings used for the three databases. If the query returned less than 500 references, all results were retained for phase 2. If the query returned more than 500 references, the first 500 were retained for phase 2. These actions identified 1,008 papers (after removing 2 duplicates) from the three databases, and they were retained for the next phase.

4.1.2 Phase 2: Artefact Identification. Results from phase 1 were screened to filter out references that did not meet at least one of the following formats: 1) Research articles published in peer-reviewed venues, written in English, and available in full text format. 2) Working prototypes, design research artefacts, or art installation previously referenced by a research article in our corpus. 3) Posters, late-breaking work, and demos. Furthermore, contents of the references (i.e., title, abstract, and/or metadata) were analyzed to filter out works that did not meet the following two criteria: 1) Mention terms related to microbes, microbiology, or particular microbial species, and imply that the focus is either investigating or enabling live-microbe based modes of human-microbe interaction. 2) Suggest that the work introduces or evaluates a concrete prototype or technology designed to facilitate human-microbe interaction. As such, works that focus on microbes but do not discuss human-microbe interaction (e.g., works that use bioinformatics to classify microbial proteins; or works that discuss probiotic consumption but not interactions) were excluded. Overall, 873 papers were removed, leaving 135 papers for full-text examinations.

4.1.3 Phase 3: Eligibility Check. Papers from previous phase were subjected to full-text examinations, and following criteria were used to identify eligible works for our final analysis: 1) For prototypes or case studies; microbial species must have been used as the core

Table 2: Search strings used in each database

Database	Search String	Filters	Results
ACM DL	{AllField:("microbe" OR "microbial" OR "microorganism" OR "micro-organism" OR "bacteri*" OR "cyanobacteri*" OR "slime" OR "yeast" OR "algae" OR "fungi" OR "fungal" OR "biodesign" OR "bioart") AND AllField: ("HCI" OR "interaction" OR "architecture")}	File Type: PDF Year: 2008-2022	1577 (500 taken)
SpringerLink	(microbe OR microbial OR microorganism OR micro-organism OR bacteri* OR cyanobacteri* OR slime OR yeast OR algae OR fungi OR fungal OR biodesign OR bioart) AND (HCI OR interaction OR architecture)	Type: Chapter Language: English Subdiscipline: User interfaces & HCI Year: 2008-2022	882 (500 taken)
IEEE	("All Metadata":microbe OR "All Metadata":microbial OR "All Metadata":microorganism OR "All Metadata": micro-organism OR "All Metadata":bacteria OR "All Metadata":cyanobacteria OR "All Metadata":yeast OR "All Metadata":fungi "All Metadata":algae) AND ("All Metadata":interaction) AND ("All Metadata":HCI OR "All Metadata":interface OR "All Metadata":architecture OR "All Metadata":biodesign) AND ("Index Terms": "human computer interaction")	Year: 2008-2022	10 (10 taken)

material component of the physical artefact, whereby livingness of the microbe component is vital to the work. The works must have featured or potentially enable human-microbe interaction. Both human-centred or microbe-centered works were considered. 2) For fabrication processes or new technologies; living microbes must have been the core material being manipulated, with the microbes continuing to stay alive post-fabrication. Furthermore, the fabrication process must have involved human intervention, or have resulted in designs that enabled, encouraged, or necessitated human interaction. Works that involved artificial microbes or microbes as part of the concept generating phase (but not the prototyping) were excluded. This process resulted in 35 papers (with 36 artefacts) for the final phase of our analysis, before supplementation (below).

4.1.4 Phase 4: Supplementation. Additional living artefacts were included for analysis, to supplement 36 artefacts that had already been screened from ACM DL, SpringerLink, and IEEE. This was to provide an even broader coverage, and as an acknowledgement that not all microbial living artefacts that are suitable for our analysis have been archived in the three particular databases. In total, 9 supplementary artefacts were identified and screened from the lead authors' personal database that consisted of 51 biodesign and bio-art artefacts accumulated over a ten year period. Whilst the 9 supplementary artefacts had passed the same eligibility check (as per sub-subsection 4.1.3), they also had to meet the following additional criteria: 1) They must have undergone a peer-review of some kind, i.e., part of a multi-authored book (e.g., [100]), and/or exhibited at an international design or arts venue that required a form of jury selection (e.g., [9]), 2) produced between years 2008 and 2022, and 3) not included in ACM DL, SpringerLink, and IEEE. Furthermore, the artefacts must have publicly available written description (e.g., as part of a website) that would allow the reader to understand how the artefact functions. Following supplementation, 45 artefacts in total were analysed (Appendix, Table 6).

4.2 Taxonomy Development

Collected artefacts were analysed and developed (in three phases) into the taxonomy in 6-month period, involving four researchers (authors) with diverse qualifications, professional backgrounds, and experiences in biodesign, HCI, and microbiology (Table 3).

4.2.1 Phase 1: Initial Categorization and Ordering. The lead author made an initial categorization and ordering for the different surfacing mechanisms, by analysing the collection of living artefacts. Over a one month period, all 45 living artefacts were analysed, using the tabulated five questions below, as a form of a codebook to guide the analysis process (Table 4). Formulated through the lead author's experiences of working with microbes in both scientific and design contexts, the set of codes and questions were identified and developed as fundamental building blocks for the taxonomy. Addressing these questions had helped the lead author to strive towards formulating the initial taxonomy with the four key desirable attributes baked into it: 1) HCI and interaction design relevance 2) microbe specificity 3) microbe-sensitivity, and 4) customizability.

4.2.2 Phase 2: Refinement. Over a 3 month period, two researchers (the first author and the fourth author) collaboratively reviewed and refined the taxonomy further, through cycles of discussions.

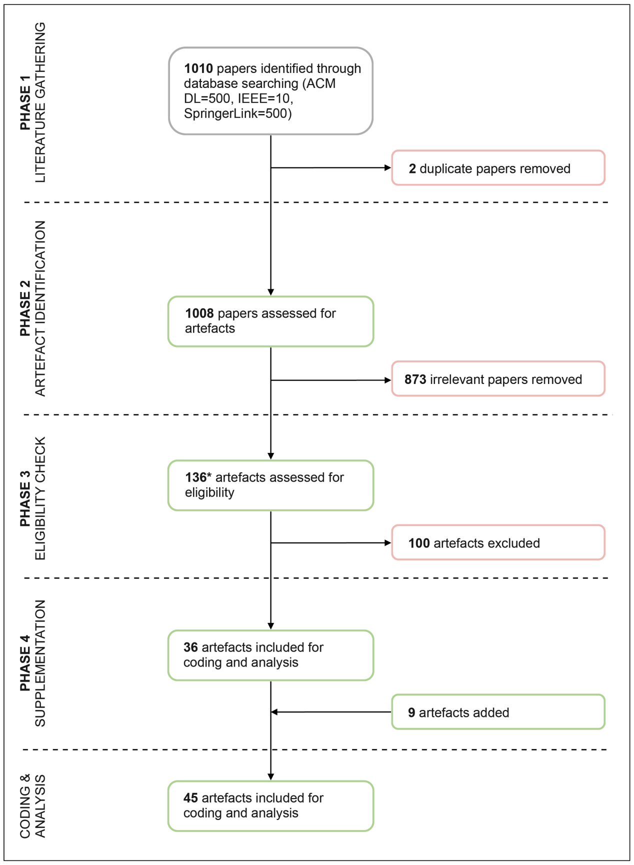

Figure 1: Flow diagram depicting systematic artefact collection process across four phases (*two artefacts were collected from one paper).

Initial categories and its order within the taxonomy were iteratively altered and reviewed through removal, addition, modification, reordering, and re-naming.

4.2.3 Phase 3: Verification. Lead author and fourth author invited two more researchers (second author and third author) to verify the refined taxonomy, with the aim to reach final consensus within the cohort. This process took approximately 2 months to complete.

Table 3: Summary of author profiles, in terms of qualification and number of years of experience in biodesign and HCI/IxD (*8 working in microbiology).

Author	Qualification	Biodesign	HCI/IxD
1st	PhD (design)	14*	7
2nd	PhD student (design)	2	2
3rd	PhD student (design)	4	2
4th	PhD (design)	10	20

5 TAXONOMY OF SURFACING LIVINGNESS

5.1 Artefacts Overview

45 artefacts that were analysed for the taxonomy development represented a diverse set of species across the microbial kingdom, including bacteria (n = 16), protists (n = 8), slime moulds (n = 5), algae (n = 4), yeast (n = 3), and fungi (n = 3). Some artefacts involved a mixture of different microbial species (n = 6). In terms of contexts and intentions with which each of the artefacts were designed; innovation of new interaction technique was evident in 31 of the artefacts, whilst evaluation of user or player experiences (UX/PX) formed a focal point for the design of 11 artefacts. Furthermore, 18 artefacts were art works, whilst 13 were designed and used as tools for education. The corpus of analyzed artefacts thus provided 1) a range of livingness deriving from diverse microbial families represented, and 2) a variety of situations, from which the surfacing mechanisms could be taxonomized and articulated.

5.2 Taxonomy Structure

Our analysis revealed six major levels of mechanisms for surfacing livingness in microbial displays: 1) *Canvassing*, 2) *Marking*, 3) *Magnifying*, 4) *Translating*, 5) *Nudging*, and 6) *Molecular Programming*. The levels have been 1) *categorized* according to the way in which microbes' livingness is surfaced, and 2) *ordered* in terms of increasing directness of designers' input and technical control towards microbes in producing the displays (Table 5).

The categorization is intended to help designers to think about different ways to curate, craft, and tune microbial displays, whilst the ordering aims to solicit broader awareness of the implications on the integrity of microbes, from implementing a particular surfacing level of their choice. We also note, that the taxonomy is not a fixed framework; categories may overlap, and ordering may be contestable. Rather, it is intended to serve as lenses for designers, inviting them to consider and to reflect on their processes of working with microorganisms. These six mechanisms are present in the surfacing of livingness of the collection of microbial living artefacts that had been analysed. In Fig. 2, we map out how these six mechanisms had been implemented within our analysed artefacts. It offers a snapshot, indicating the diverse ways with which designers have applied various surfacing mechanisms form their organisms under investigation, and in relation to the different biological phenomena involved in the livingness surfacing processes.

5.2.1 Non-Anthropocentric Essence. Accompanying each level of the taxonomy is a statement which is called non-anthropocentric essence. The idea behind this came about through a conversation between the first and the second author during the refinement phase of the taxonomy development. In fact, these were actually used as an internal memo to help us maintain a microbe-sensitive, and a human de-centered approach during the taxonomy formulation. We first asked ourselves, *"how, and in which order, would a microbe prefer to be surfaced for noticing by humans?"*, and then reflected on how we (humans) would in turn respond to such preferences from the microbes. We decided to keep these essences as part of the taxonomy, as they could also help and inspire designers in their respective collaborations with microbes.

Table 4: Codebook for initial categorization and ordering

Code	Guiding Questions
Livingness	*What is/are the type(s) of surfaced livingness in the artefact (e.g., growth)?*
Agents	*What were the respective roles of human, microbe, computer, in the display creation?*
Microbe-Sensitivity	*Which microbe-specific surfacing constraint(s) (Table 1) was/were being addressed?*
Microbial Integrity	*To what extent did the display creation compromise the integrity of the microbe?*
Customizability	*How modular and/or adjustable were the mechanisms for the display generation?*

Table 5: Taxonomy of microbial displays (with accompanying non-anthropocentric essences)

Level	Category	Non-Anthropocentric Essence
1	Canvassing	*"Setting the scene and observing"*
2	Marking	*"Marking around the organism"*
3	Magnifying	*"Coming forward a little closer"*
4	Translating	*"Figuring out what microbes are trying to say"*
5	Nudging	*"Giving them a nudge and see how they respond"*
6	Molecular Programming	*"Re-configuring their genetic makeup"*

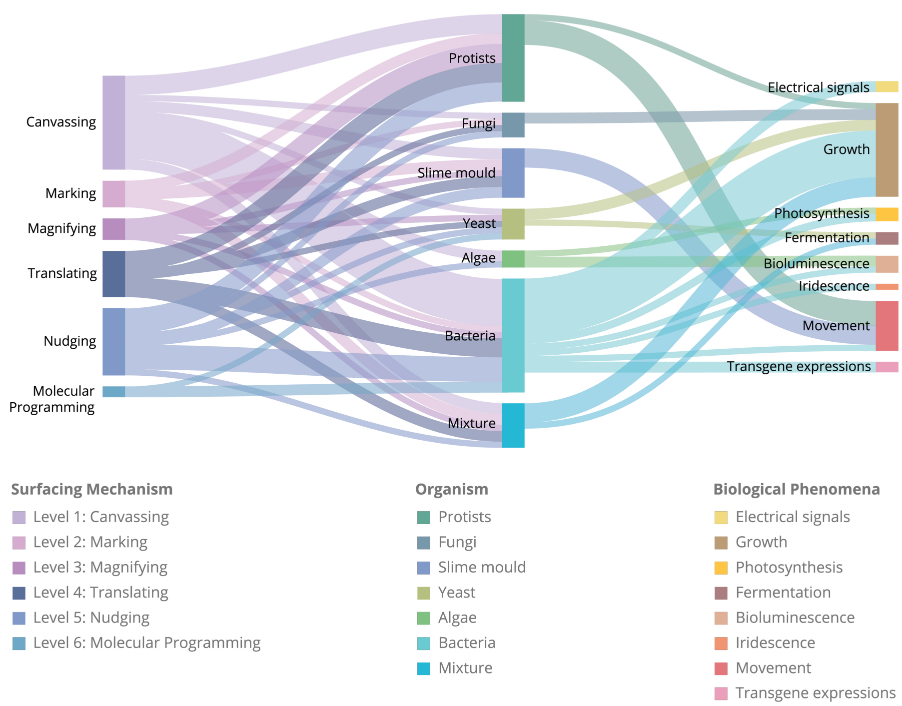

Figure 2: Sankey diagram illustrating flows of three sets of components involved in livingness surfacing, generated from further analysis of the 45 microbial living artefacts. Thickness of lines are in proportion to the number of incidences.

In the following subsections, we outline and unpack each taxonomy level and its underlying mechanism. Using existing cases in biological-HCI as references, we describe how the six levels help to surface livingness of microbes, whilst highlighting possible ways with which each level can be tuned towards producing a variety of design outcomes.

5.3 Level 1: Canvassing

At level 1, *Canvassing* is an initial step for designers towards surfacing livingness of microorganisms. We describe it as a proactive process of framing a microbial habitat; of designing and providing a "canvas" onto (and within) which microbes can live and express their livingness over time (Fig. 3).

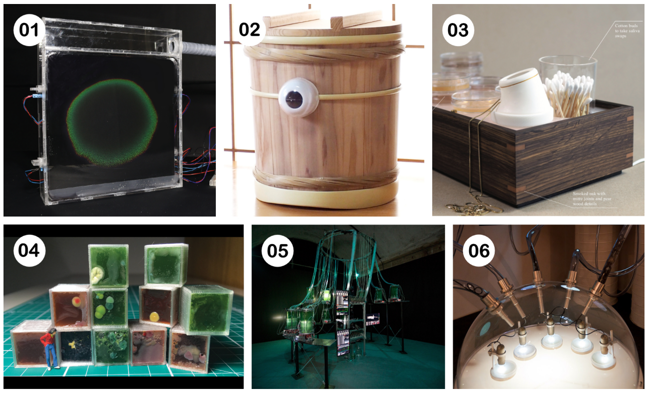

Figure 3: Canvassing examples in biological-HCI. 1: Contained, transparent canvas of *Flavorium* [46]. 2: *Tsukumogami* style, wooden bucket of *Nukabot* [20]. 3: Craftsmanship-infused lightbox and *Loupe* for microbiome tracking [10]. 4: 3D-printed cubic canvases for moulds, creating unusual cornering growth behaviours in *MouldCraft* [72]. 5: Large-scale installation with extending computer hardware and silicone tubing in *CMD* [120]. 6: Metal-glass combination that extend the canvas for *C. elegans* containment in *Microscopic Opera* [99].

In microbial living artefacts of biological-HCI, most of the canvassing process involved some form of containment (e.g., a Petri dish) as a way to isolate the microorganism, and to create a sealed border between the organism and the outer environment (e.g., [21, 46, 99], Fig. 3.1).

That said, however, canvases that are less sealed, with a relatively more open and bio-receptive set up, have also been implemented in biological-HCI with interesting results, highlighting further design opportunities for the community. Ofer et al. [105]'s explorations with *Dinoflagellates* under semi-open and porous environments for example, demonstrated how shifting the aperture and receptivity of the canvas, had offered diverse ways with which the algae displayed its livingness in the form of bioluminescent patterns. Similarly, Kim et al. [76] have reported how an accidental relaxing of containment during a biotic game had introduced airborne contaminants to overtake the microbial display, producing unintended yet arresting alterations to the game mechanics.

In terms of the canvas *material* itself, most have been those that are widely used in scientific research. These included transparent plastic and glassware such as culture dishes and conical flasks, and semi-solid growth platforms such as agar. However, we highlight below some of the unconventional materials that we found to have been used (Fig. 3.2 and 3.3), to inspire designers to consider alternative materials for designing, and to help them strategize ways of tuning their displays. These artefacts opted for non-transparent materials such as wood (Fig. 3.2 and 3.3). Designers of these artefacts explained how using traditional materials and applying craftsmanship to its construction, had brought an extra layer of cultural meaning to the final design, elevating status of inhabiting microbes to a higher level, encouraging their appreciation and care [10, 20].

In addition, changing not only the composition but also the *shape* of the canvass (e.g., from circular to square, as seen in Fig. 3.4), have been shown to generate unexpected microbe-containment interactions [72], whilst *ancillary* materials that extend from the canvas (Fig. 3.5 and 3.6), such as computer hardware, tubing, and metal-glass combinations, have been implemented to affect how users would perceive and engage with microbial displays.

5.4 Level 2: Marking

Markings are defined as coloured lines, shapes, or patterns on the surface of something, which help to identify and/or display certain characteristics. As a practical, cost-effective, and an often non-invasive way of displaying messages, markings can be found in our daily lives. An elastic band around a jar of live sourdough culture for example, helps the baker to anticipate and to notice the livingness of yeast within, as the dough rises through fermentation over time. Markings that are made without digital technology may be quicker and easier to implement, although digital markings, such as those created from image tracking software, may offer better flexibility in terms of being able to change with time and according to fluctuations of microbiological outputs.

Our analysis identified three different types of marking that had been implemented towards producing microbial displays in biological-HCI (Fig. 4): *temporal marking*, *background marking*, and *accent marking*. These sub-types may help designers to address some of the microbial surfacing constraints, as well as to better articulate potential nuances within the display.

Temporal markings are forms of visual references and cues that may help people to relate data of the past, present, and the future. This is a useful way to sense changes in microbial activity that may be difficult for humans to track in real-time. For example, in *Interactive Cloud Experimentation for Biology* (Fig. 4.1), slow migratory behaviour of slime moulds (towards food sources) were digitally tracked and marked. This provided a historical digital trace of the organism's movement across just a few centimetres that had manifested over several hours which would not have been noticeable to humans in real-time. In contrast, microbial responses that are too fast for the human eye (e.g., spontaneous and microscopic shifts of euglena cells) were also addressed through temporal marking in *Luduscope* (Fig. 4.2). As such, temporal marking could help designers to overcome surfacing constraints of slow (as well as excessively fast) microbial response times. Temporal markings may also provide a visual reminder that a microbial change *is* occurring, as well as for the changes that *will* occur. In *Mould Rush* (Fig. 4.6), a set of static, graphic overlay symbols (e.g., a skull and a flying bomber) were used to temporally mark a past microbial event (skull = death) and a future microbial event (flying bomber = pending death). Here, the markings served as a constant, ever-present reminder to the audience of the artefact, of the livingness of the microorganisms.

With *background marking*, designers can add texture or colour to the background of microbial displays. These are intentionally placed visual forms that set the scene of an interaction, giving context to a particular human-microbe interaction. In *Playscope* (Fig. 4.4) for example, a virtual soccer pitch marks the background, indicating gamified interactions involving euglena, and similarly in *Pac-Euglena* (Fig. 4.5), maze-like textures created by walls of

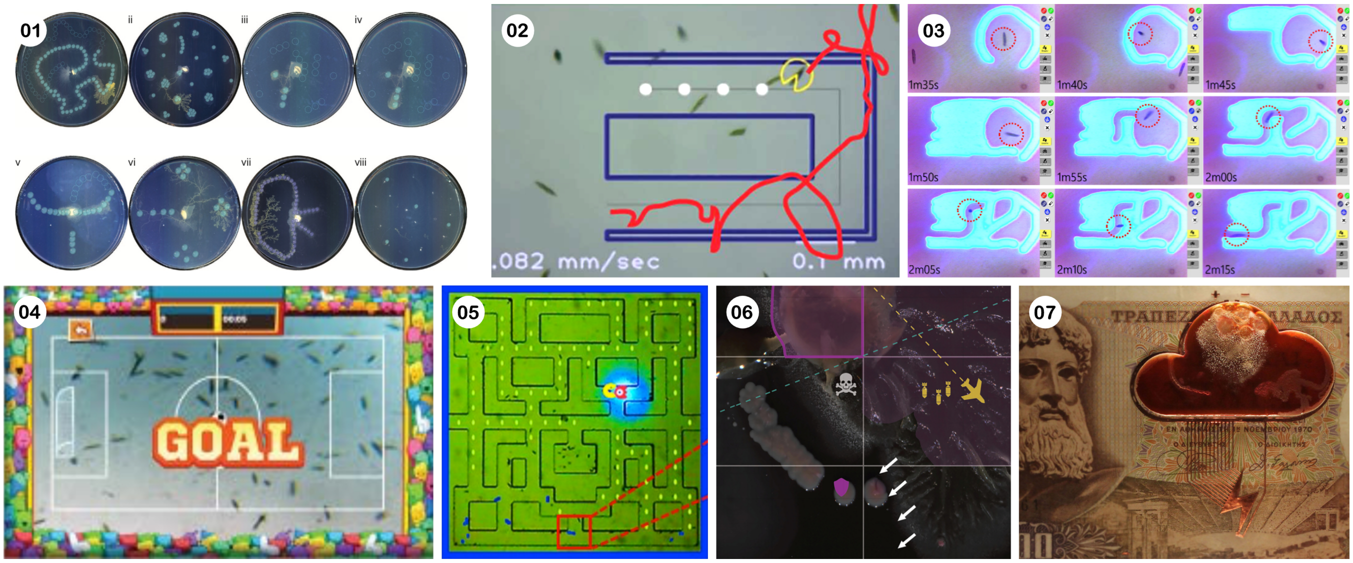

Figure 4: Marking examples in biological-HCI. 1: Gradual migration of slime moulds towards food were digitally marked in *Interactive Cloud Experimentation for Biology* [59]. 2: Red line marks the spontaneous and quick movements made by euglena cells in *Luduscope* [68]. 3: Bright lines accentuate human-microbe interactions in *Trap It!* [87]. 4: Soccer pitch overlay used to create a playful backdrop in *PlayScope* [82]. 5: Maze-like structure forms a gaming background in *Pac-Euglena* [79]. 6: Graphic overlays mark the past and the future of microbial livingness in *Mould Rush* [75]. 7: A lightening bolt marks around a microbe habitat to accentuate microbial growth in *Reviving Drachma* [69].

microfluidic chambers that contain the microorganisms signal that a game is taking place. Background markings provide a visual context of interaction (e.g., a fast soccer game), helping to indicate expected microbial behaviours and any potential interaction constraints that would need to be prioritized and/or resolved to meet the design goals (e.g., focusing on overcoming potentially slow responsiveness).

Accent Marking helps to accentuate, emphasize, or highlight parts of microbial displays. In *Trap It!* (Fig. 4.3) and *Human-Microbe-Interactive* (HMI) dance [80], user inputs (made via their bodily movements) are accentuated through brightly coloured lines on the monitor screen. They provide visually engaging patterns for the users. Similarly, the bright blue glow around euglena as observed in *Pac-Euglena* (Fig. 4.5) also provides visual interest which may help to improve user experiences of living artefacts. Similarly, in *Reviving Drachma* (Fig. 4.7), a copper-tinted bolt of lightning is embedded under an area of microbial growth. This added drama to the microbial activity happening above, and helped to create an additional layer of meaning to the microbial activity.

5.5 Level 3: Magnifying

Magnifying (Fig. 5) is defined as the act of causing objects to appear larger than they really are [23]. Within biological-HCI, we have identified two tactically similar (and often overlapping) ways with which designers have applied magnification to surface livingness of microbes: *Practical magnification* and *Aesthetic magnification*. We propose that designers could switch between, or combine these types of magnifications, as a way to tune their design goals. With *practical magnification*, the intention behind the magnification would be primarily to simply bring microbes that are normally invisible (to the naked human eye) to become visible. In *Microscopic Opera* (Fig. 5.2) for example, the designer used magnifying as one of the ways to make microscopic movements of *C.elegans* visible to the human observers.

Aesthetic magnification on the other hand, brings different emphasis to microbial displays, by focusing on *stylising* how the enlarged microbes appear to the observer(s). For example, in *Luduscope* (Fig. 5.4), *Human-Microbe-Interaction-Dance* (Fig. 5.3), and *BioGraphr* (Fig. 5.5), magnification levels were calibrated to not only ensure euglena's visibility, but also to control how fast or slow their movements appeared on a monitor screen. Since applying magnification that is too low can make movements of cells seem sluggish, and that magnification that is too high can render the movements too fast to be noticeable, designers of these artefacts considered magnifying microbes beyond visibility, and towards exploring how our interactions with microbes could be better experienced.

Similarly, as demonstrated in *Loupe* (Fig. 5.1), *Mould Rush* (Fig. 5.6) and *Interactive Cloud Experimentation for Biology* [59], the designers gave priority to the visual tone of the magnified microbes over their visibility, a type of strategy that some researchers have called *"resolution over magnification"* ([73], p.3) in creation of microbial displays. The intent here was not only to just "zoom in", but also to deploy a certain degree of artistry to support visual appreciation of microbial phenotypes. The fine morphology, textures, colours, and opacity of microbial species were brought to the fore, through tuning of the resolution and light exposure of the artefacts' magnifying components; achieved through uses of 1) high-resolution

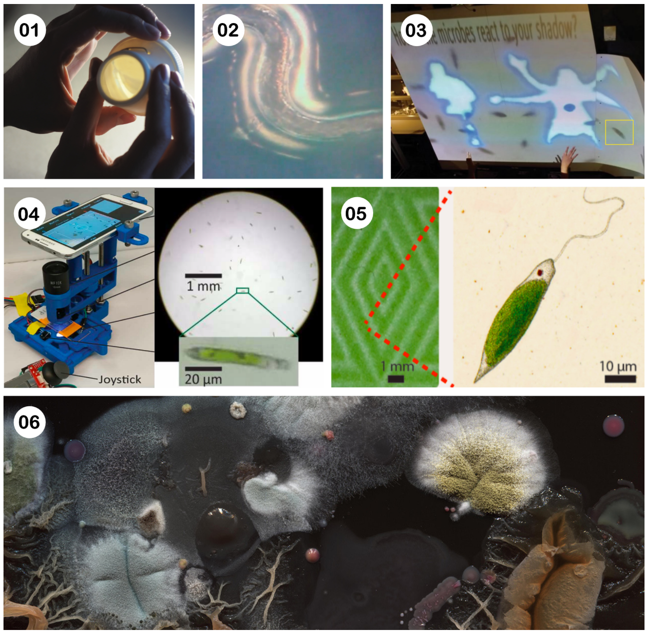

Figure 5: Magnifying examples in biological-HCI. 1: Rotating magnifying lens with transparent base material of *Loupe* [10]. 2: Magnification enables viewing of microscopic movements made by *C. elegans* in *Microscopic Opera* [99]. 3: Magnified euglena cells on display with dancers in *Human-Microbe-Interactive Dance* [80]. 4: Combination of closed-circuit television (CCTV) broad lens and standard 10x eyepiece helps to calibrate magnification of euglena in *Luduscope* [68]. 5: Magnified euglena in *BioGraphr* [39]. 6: High-resolution (scanned) image of mould growth as a way to frame battlegrounds of a biotic game, in *Mould Rush* [75].

scanning device ([59, 75]), 2) a rotating lens [10], and 3) transparent grounding materials that allowed back-lighting to shine through (to help surface translucent microbes) [10].

And lastly, as a side note: in some cases, magnified images and video had been made to supplement an existing microbial display (e.g., [39]). They were mostly static images and/or pre-recorded videos of magnified microbes that had been displayed in close proximity to the main microbial display. They did not surface livingness of microbes in the main display directly, although they had nevertheless been used to draw potential observers towards the artefact containing the microbes.

5.6 Level 4: Translating

Translating is defined as the rendering of something into another language, or into one's own from another language [23]. In artefacts of biological-HCI, livingness of microbes is often surfaced through translation of microbiological phenomena into digital outputs. For example, in *Bio-Electronic Soil Sensing Device* (Fig. 6.1), conductivity and voltage potential (energy) generated by bacterial activity were translated into Arduino-controlled series of coloured LEDs, whilst in *Microbial Content Generation* (Fig. 6.2), the designers

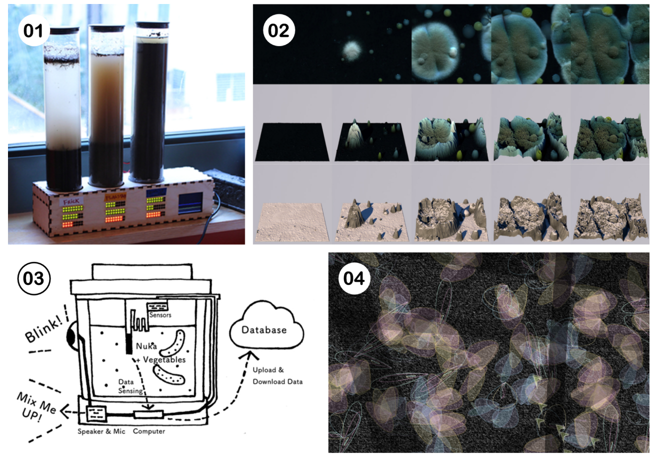

Figure 6: Translating examples in biological-HCI. 1: Soil incubator columns coupled with green and red LED actuators that translate bacterial metabolic activities, in *Bioelectronic Soil Sensing Device* [78]. 2: Translation of microbial growth into evolving virtual 3D game terrains, in *Microbial Content Generation* [81]. 3: Lactic acid bacterial activity translated into digitized human voice and speech, in *Nukabot* [20]. 4: Translation of real-time microbial metabolism as dynamic, spontaneous, and colourful animations in *ALICE* [3].

demonstrated that progressive microbial growth could be digitally captured and rendered into an evolving 3D virtual gaming terrain. Similarly, in *Nukabot*, fermentation activity of lactic acid bacteria were translated into digitized human speech and voice (Fig. 6.3), whilst in *Active Living Infrastructure: Controlled Environment* (*ALICE*), electron flows generated by microbial metabolism were translated by a computer software in generating colourful, real-time animations (Fig. 6.4).

Translating is a possible way to help designers to overcome several microbe-specific surfacing constraints. As demonstrated in *ALICE*, cellular electron flow translation can offer a spontaneous (real-time) way of surfacing (through visualization) bacterial metabolisms that would be too minute and too slow for humans to notice without an appropriate translation technique [3]. Furthermore, conversion of fermentation levels into human speech and voice as observed in *Nukabot* suggest a potential of anthropomorphization as a persuasive technique for designers to soften the quality of microbial displays that would otherwise provoke negative feelings from the viewers [20]. Digital translation on a practical level, it can also be shared online (e.g., to widen user/audience base), easily copied and stored, and connected to wide-ranging actuators (e.g., as seen in [59]). Such possibilities not only increase the overall accessibility of microbial artefacts, but they also help people to experience livingness of microbes that may be pathogenic and unsuitable for direct contact (as highlighted in [75], p.6).

5.7 Level 5: Nudging

Nudging can be defined as an act of touching or pushing (something) gently or gradually [23]. Through nudging, we invite (and sometimes impose) microorganisms to shift their physiology and/or

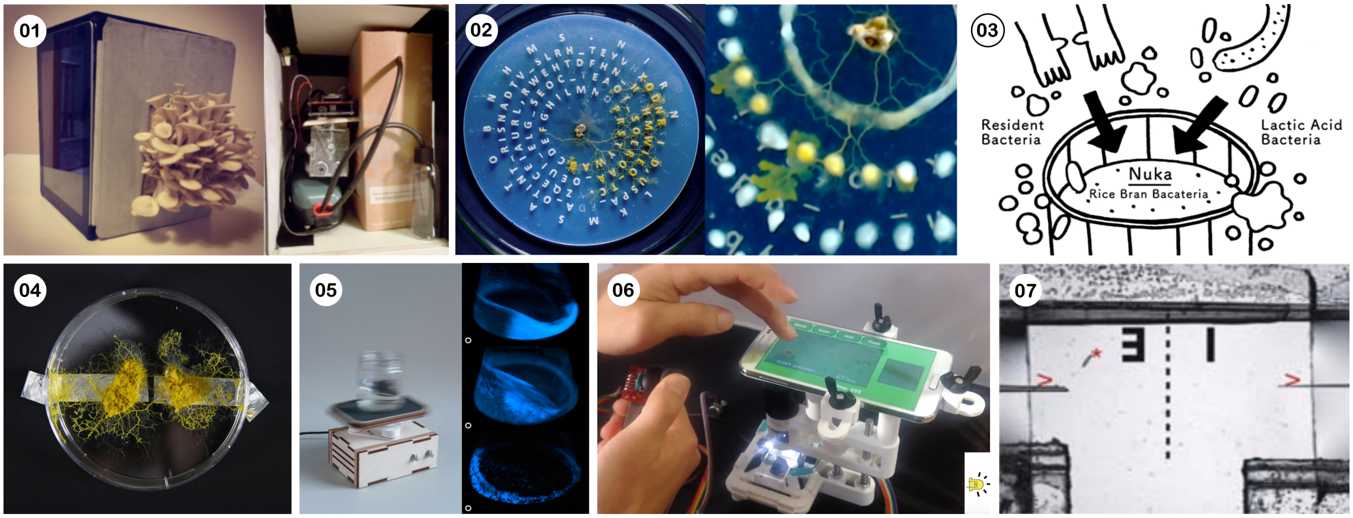

Figure 7: Nudging examples in biological-HCI. 1: Watering nudges mushrooms to grow, in *Rafigh* [48]. 2: Alphabets made from oats nudge the microbe to migrate from the centre of a culturing dish, in *Slime Mold Andi* [94]. 3: Hand stirring of rice bran nudges bacterial communities to stay healthy and to encourage fermenting vegetable flavour development, in *Nukabot* [20]. 4: Two food sources connected by a protoplasmic tube nudge slime moulds to create movement patterns, in *Ctrl* [119]. 5: Varied forms of agitation nudge *Dinoflagellates* to produce different bioluminescence patterns, in *Living Light Interfaces* [6]. 6: LED lights nudge *Euglena* cells to swim away from the light, in *Luduscope* [68]. 7: Chemicals dispensed through microneedles are used to nudge *Paramecia* away from one area of a culture dish to the other, in *POND PONG* [116].

behaviour, to an extent that would make the livingness more noticeable to the human senses (Fig. 7). Nudging of microbes are often initiated by exposure of the organisms to various types and quantities of environmental, chemical, and mechanical stimuli, which may trigger noticeable biological response(s). In artefacts of biological-HCI, various stimuli and biological responses have been involved in nudging.

In *Rafigh* (Fig. 7.1), water was used to nudge the growth speed of fungi, allowing changes to their fruiting bodies to become more noticeable. Meanwhile, some artefacts have used food as a nudging material to encourage microbes to move from one location to the other (Fig. 7.2, and 7.4). Furthermore, manual forms of nudging have also been explored. In *Nukabot* (Fig. 7.3), bare human hands are used to stir (and to nudge) a fermenting rice bran mixture, to promote healthy bacterial growth whilst improving flavour of fermenting vegetables; thus forming a part of mutualistic care practice between humans and lactic acid microbiota. In *Living Light Interfaces* (Fig. 7.5) and other similar artefacts involving bioluminescent microbes (e.g., [105, 117]), livingness as a bioluminescent glow was surfaced through physical agitation. And lastly, in artefacts such as *Luduscope* (Fig. 7.6) and *POND PONG* (Fig. 7.7), light and chemicals respectively, were used to trigger dramatic and visible movement responses from microorganisms.

The intensity with which microbes are nudged can be adjusted, to tune the quality of microbial displays. For example, temperature inside an incubator could be increased to speed up microbial growth (e.g., [75]), and increased levels of agitation may produce brighter glows in bioluminescent algae (e.g., [6, 105]). Whilst nudging can offer enhanced human control towards how microbial displays could be generated, increasing the intensity of the nudge may compromise microbes' agency and/or integrity, and may harm or kill the organisms in the process.

5.8 Level 6: Molecular Programming

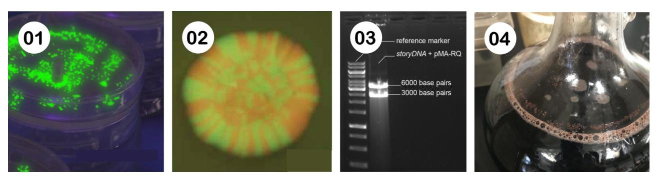

Figure 8: Molecular programming examples in biological-HCI. 1: Genetically modified *E.coli* under UV light, in *Empathetic Living Media* [21]. 2: In *Prisoner's Smellemma* [116], green and red fluorescence genes are inserted into two yeast strains to distinguish one from the other when mixed. 3: Electrophoresis gel showing DNA encoded with a personal story. The DNA was inserted into bacteria *Komagataeibacter rhaeticus*, in *Semina Aeternitatis* [2]. 4: Poetry-infused wine, resulting from yeasts containing encoded DNA, in *Raaz* [50].

Molecular programming is part of a genetic modification process that combines computation theory and molecular biology to create DNA-based structures, circuits, and devices [47]. The programmed DNA, constructed through molecular biology techniques, is inserted into microorganisms to transform the organism. Molecular programming can potentially help microbes to surface their livingness through addition, removal, enhancement, and alterations of their capabilities and/or functionalities.

In biological-HCI, molecular programming has been implemented in several artefacts (Fig. 8). In *Empathetic Living Media* [21], *E.coli* bacteria were transformed with two foreign genes: one that coded for Green Fluorescent Protein (GFP), and the other for antibiotic resistance. The modifications had rendered the bacteria more noticeable to the human eye. The microbes could produce a distinctive green glow (Fig. 8.1), and they could also thrive in antibiotic-rich habitat that would have eliminated any potential contaminating and/or competing bacterial species around the habitat. Similarly, in *Prisoner's Smellemma* [116], green and red fluorescence genes were programmed and inserted separately into two batches of yeast. This meant that respective levels of growth of yeast cells from each batch, as indicated by the amounts of green and red fluorescence produced, could be easily distinguished from one another when the two batches were mixed together (Fig. 8.2). Furthermore, works such as *Semina Aeternitatis* (Fig. 8.3) [2] and *Raaz* (Fig. 8.4) [50] involved encoding of a personal story (*Semina Aeternitatis*) and a poem (*Raaz*) into synthetic DNA, which were subsequently transformed into microorganisms. Here, the works highlight a potential for extrabiological (i.e., non-genetic) information to be used to alter how humans perceive and experience livingness of microbial growth and fermentation.

Whilst these examples can be regarded as relatively simple, "local" modifications involving plasmid-based DNA circuits, current technology (e.g., *CRISPR/Cas9*) offers the possibility for more complex and "systemic" (genomic) alterations in microbes to be made. From adding cellulose-digesting capabilities (e.g., [133]) to adding new movement patterns in microbes (e.g., [132]) and creating customized scents from microbial metabolism (e.g., [97]), etc., molecular programming can offer highly specific and customizable means to alter microorganisms' behaviours, and thus shape how their livingness is surfaced. However, molecular programming may also significantly alter microbes' integrity, whilst associated technical and biosafety challenges may limit biodesigners from future access and implementation of molecular programming.

6 TAXONOMY IN ACTION

6.1 Case of Flavobacteria

We present a case study of Flavobacteria. Led by two biodesigners experienced in designing with the particular organism (i.e., the second and third authors), the study was undertaken shortly after development of the taxonomy. The aim was to demonstrate how the taxonomy could be applied in strategizing how livingness of microorganisms could be best surfaced. The case study focused on Flavobacteria's genus *Cellulophaga* [66] (from hereon, referred to as Flavobacteria): a non-pathogenic type of marine bacteria noted for their ability to produce colourful displays of vivid iridescence through growth-induced crystal structure formation [67]. The biodesigners first analysed Groutars and Risseeuw et al.'s work in HCI, titled *Flavorium: An Exploration of Flavobacteria's Living Aesthetics for Living Colour Interfaces* (2022) [46] (Fig. 9), which explored Flavobacteria's design potential as a responsive medium. Under the lens of the taxonomy, the biodesigners discussed the work, in terms of surfacing levels that had been explored (and unexplored) in surfacing Flavobacteria's livingness. Through the expertise of (microbe-focused) biodesign and interaction design as provided by the second and third authors, we analysed and articulated our findings in terms of design implications for HCI.

6.1.1 *Surfacing Mechanisms in Flavorium.*

The biodesigners identified three levels of surfacing mechanisms that were evident across all three artefact variations of *Flavorium* (Fig. 9). These levels were *Canvassing* (level 1), *Marking* (level 2), and *Nudging* (level 5).

For canvassing, a closed form was used in the artefacts, whereby the bacteria had been isolated and cultured inside a sterile and controlled environment within which livingness could surface over time. In terms of marking, adding black pigments to the normally colourless nutrient agar platform helped with the surfacing process. Here, the darkening of the backdrop of the habitat accentuated the outer edges of the Flavobacteria colony, hence bringing forth the microbes' peripheral collective anatomy, which would have been difficult to observe otherwise. As the colony grew and started to expand outwards, its living aesthetics were thus made more prominent and noticeable to the observers.

Lastly, the microbes had also been nudged, in three different ways. Firstly, the act of transferring Flavobacteria from their natural marine habitat to an artificial one, had nudged the microbes to produce iridescence. This is because Flavobacteria cannot produce iridescence in marine (i.e., mostly liquid) environments; the structural organization process involved in the colouration is facilitated by the semi-solid property of the agar medium, which effectively nudges the process to occur. Secondly, changes in humidity levels of the habitat had nudged Flavobacteria to change its growth patterns in *Living Label* and *Living Monitor* (Fig. 9.1 and 9.2), as the microbes are sensitive to such environmental changes. And thirdly, Flavobacteria were manually nudged, in *Living Notes* (Fig. 9.3), through writing of "invisible notes" with a solution containing Flavobacteria. The notes appeared over time through the livingness of the organism, revealing particular textual patterns with which the cells had been initially spread across the agar surface.

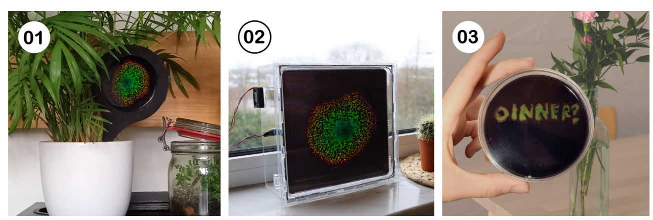

Figure 9: Three living artefacts of *Flavorium* [46]. 1: *Living Label*, indicating well-being of a house plant. 2: *Living Monitor*, representing physical activities of a person. 3: *Living Notes*, enabling playful back-and-forth communication.

6.2 Crafting Flavobacterial Displays

The biodesigners analyzed how the diverse set of modular and adjustable mechanisms offered by the taxonomy could not only help biodesigners to address the potential technical, practical, and semantic challenges (Table 1) in surfacing livingness of this particular species, but also to explore how these mechanisms could be used strategically to accommodate possible new stakeholders and their values. *Canvassing*, *marking*, and *nudging* mechanisms already deployed in domestic applications of Flavobacteria as seen in Fig 9 may be appropriate for fostering relatively predictable, slow, and ambient human-microbe interactions. Yet designing for different users, contexts, and environments may warrant microbial colonies to behave with less predictability and/or with higher dynamism, requiring an alternative combination of mechanisms. The following presents three interaction concepts involving Flavobacteria, demonstrating the adjustable and multi-layering capabilities of the taxonomy, in action.

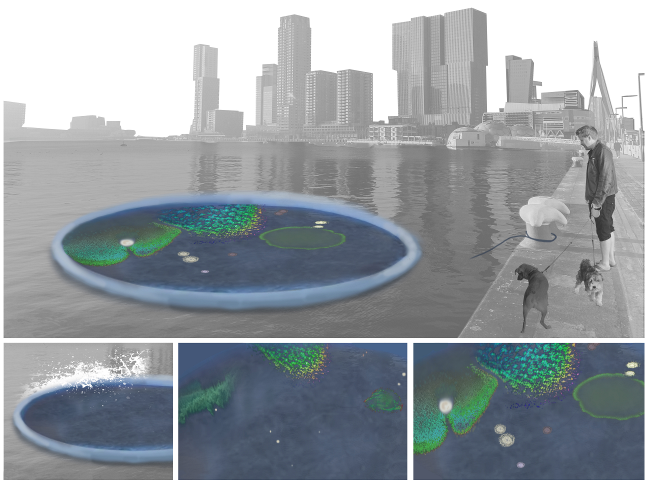

Figure 10: *Flavo in Situ* (concept 1). Top: Circular canvas displaying microbial growth. The canvas is made from semi-solid agar material, and it is left open and exposed to the sea, a natural habitat of Flavobacteria. Bottom, left: Multiple microbial species from seawater (including Flavobacteria) enter the canvas through a wave. Bottom, middle: Agar in the canvas nudges Flavobacteria to surface iridescence as they grow. Bottom, right: Multi-species interactions between Flavobacteria and other species is surfaced.

6.2.1 Concept 1: Flavo in Situ. Alternative methods of *canvassing* (level 1) Flavobacteria can provide very different expressions of livingness and associated user experiences. In *Flavorium* [46], Flavobacteria's livingness had been surfaced by means of isolation and closed canvassing, creating a sealed border between the organisms and the outer environment. However, one can also envision more open, *in situ* canvassing that invites multitude of other microbes that inhabit Flavobacteria's natural habitat (Fig. 10). This would allow for diverse and unexpected interactions between Flavobacteria and others to unfold, thereby surfacing diverse forms of livingness, both complex and serendipitous in nature. These multispecies interactions could produce an arresting display of symbiotic and/or competitive behaviours, in which Flavobacteria may reveal their ways of scavenging (using dead cells as nutrients) and predation (using living cells as nutrients) [51]. Such scenarios could, therefore, not only facilitate human noticing of Flavobacteria's presence and their everyday interactions, but also surface livingness of others within an ecological assemblage, thus potentially contributing towards sharpening our ecological sensibilities.

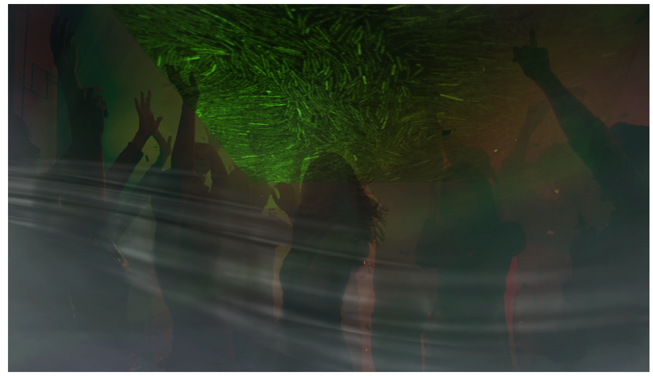

Figure 11: *Flavo's Night Out* (concept 2). A night club dance floor, which accompanies clubbers and music with a magnified and ceiling-projected live footage of swimming Flavobacteria. The microbial movements are also translated into direction and intensity of ventilation air flow.

6.2.2 Concept 2: Flavo's Night Out. Here, the biodesigners explored ways in which *magnifying* (level 3), *translating* (level 4) and *nudging* (level 5) could be introduced, either on their own or in combination; as a way of crafting the quality of a Flavobacterial display. Although canvassing (level 1) already allows Flavobacteria's structural colour (iridescence) to be made noticeable to the naked human eye, this concept presents additional ways to extend the modality with which we could perceive this livingness.

The concept starts from level 3 (magnifying), zooming in closer to the microbes. At the magnified level, one can observe the motility of the Flavobacteria cells, constantly adjusting their positions to form highly-organized optical structures that ultimately result in the microbes' iridescence. In other words, observers of magnified microbes would see the *process* of colour formation, as opposed to its end result. Interestingly, Flavobacteria move at a surprisingly fast pace, able to move twice their body length per second [11] (see supplementary item). Magnification can thus alter the way in which humans experience Flavobacteria's living aesthetics. From slow, gradual changes in colour over several hours (when viewed without magnification), to fast and immediate changes through magnification.

The biodesigners propose that deploying magnification, especially in combination with translation, could allow humans to experience Flavobacteria's livingness in relatively direct and spontaneous ways: For example, when integrated as a backdrop of a night club (Fig. 11). Here, real-time magnification and ceiling projection of Flavobacteria would greet the clubbers, as a dynamic visual accompanying their dancing. Simultaneously, bacterial movements could be translated through integration of digital sensors that control and actuate the venue's ventilation system; manifesting as changes in direction and intensity of air flow on the dance floor.

The system would also generate a form of reciprocal nudging (level 5) between clubbers and the host bacteria, where the dancers would generate bodily heat, that would incite the microbes to swim faster. This would increase the intensity of the projected motility, but also the power of the ventilation, which in turn would timely cool down both the clubbers and the critters alike.

6.2.3 Concept 3: Environmental Modification. Mechanism of *Molecular Programming* (level 6), specifically through genetic modification, could offer an array of new expressions and ways of surfacing Flavobacteria's livingness. Whilst programming of Flavobacterial behaviour is yet to be implemented by designers, professional microbiologists have been doing so for some time (e.g., [62]). These point towards the possibilities to program Flavobacterial colour and their sensitivity to chemical and environmental stimuli. Whilst molecular programming would likely to interfere with Flavobacteria's default genetic blueprint, it would nevertheless enable designers to program Flavobacterial displays with a high level of precision and granularity. For instance, by programming the microbe to express particular colours at specific locations of a culture plate and at specific time-points, designers could craft the microbes to create a familiar image that may encourage humans to take notice and to anticipate Flavobacteria's livingness.

Envisioned is a living public display of planet Earth in various phases of geographical change (Fig. 12). Different genetically programmed strains would generate different colours, allowing for spatial control over these colours and the representation of continents and oceans. In addition, programming Flavobacteria to react to chemical stimuli will render the display responsive to environmental change. Such stimuli, such as volatile compounds or pollutants in the surrounding air, could trigger certain genetic pathways, leading to different behaviours such as expansion, colour shifts, and even death. This living visual metaphor of our planet, will thus change in appearance due to the livingness of the organism, representing the precarious state of our planet as a whole. Overall, the biodesigners acknowledge that this concept may be perceived as an extreme example of the taxonomy in action, involving significant changes to Flavobacteria's genetic makeup and the autonomy of the organism. Yet the concept also illustrates the fact that some extreme situations (e.g., climate change) may warrant provocative measures (on a molecular level) to engage people.

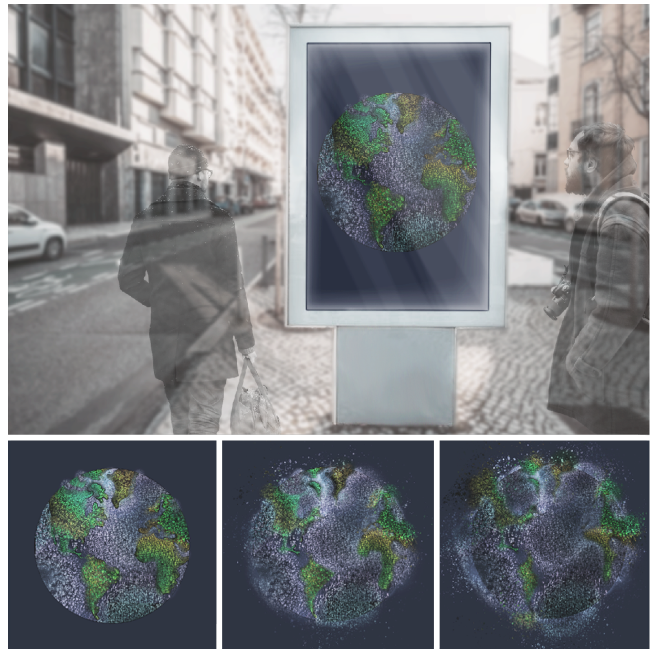

Figure 12: *Environmental Modification* (concept 3). A living public street display, canvassing a live Flavobacteria culture mix, that is nudged in the shape and colours of oceans and continents of planet Earth. The microbes are genetically modified to sense changes in air quality. Increased pollution levels trigger pre-programmed behavioural changes in Flavobacteria, resulting in shifting displays of the Earth, designed to provoke and alarm passers-by.

7 DISCUSSION

In this paper, we have responded to the proliferation and diversification of microbe-based living artefact explorations in HCI, and the overall lack of existing microbe-appropriate design frameworks in their support. Through the development of *Taxonomy of Surfacing Livingness in Microbial Displays*, we offer HCI and interaction designers a set of microbe-appropriate lenses towards surfacing microbial livingness; a material quality inherent in living artefacts, fundamental to not only of their operation but also towards enriching how we can and might interact with the non-human agents of today and tomorrow. The following highlights main findings of our work, and discuss their implications in HCI and interaction design.

7.1 Diverse and Adaptable Ways of Surfacing Livingness

By offering a set of multiple and diverse types of mechanisms with which microbial livingness can be surfaced, the taxonomy is geared towards empowering biodesigners with broader awareness, for them to make informed decisions when designing living artefacts. Green fluorescent hues emanating from genetically modified animals may have had its allure in the early 2000s (*GFP bunny* [63]), designers may need to look beyond novelty of genetic modification in surfacing livingness of microorganisms, to be mindful of ethical and safety implications of their practices, and towards engaging with an increasingly biotechnology-aware generations of potential users of living artefacts. Besides, we argue that bacteria as an empathetic living media as demonstrated by Cheok et al. in 2008 [21], could have achieved similar outcomes through deploying mechanisms alternative to the (multiple) foreign gene additions used. Lowering the taxon from *molecular programming* (level 6) to *translating* (level 4) or even to *marking* (level 2), the UV-induced glow integral to empathy induction could have been digitized, thus mitigating the potential practical, ethical, and safety challenges associated with microbial transformation and visualization. Through digitally marking and translating potential livingness changes in *E.coli*, genetic integrity of the microbe would be retained, whilst also avoiding harmful effects of ultraviolet light on both the bacteria and their observers.

That said, the diversity of the taxonomy also means that the taxon level used could also go in the opposite direction, from lower to higher levels. Compromising the integrity of the microbe, *molecular programming* (level 6) for example might be a carefully calibrated decision towards communicating certain urgent messages (as highlighted in Flavobacteria concept 3), or that it would be the only remaining choice to resolve potential hurdles that may limit how living artefacts could be used. Livingness could be displayed (e.g., as glowing distress signals, or as way-finders ([6], p.1217)) in dark and/or extreme environments: from arid lands, polluted oceans, to even amongst ionizing radiations of the outer space. Environmental resilience could be programmed into microbes, for example in the form of transfer of genes from natural extremophiles (e.g., [126]), to ensure a much-needed and timely collaborative human-microbe survival [89].

Furthermore, responding to calls in the wider HCI community towards improving *accessibility* in design, the taxonomy recognizes diverse physical and neurological abilities amongst potential users of living artefacts. Not everyone can appreciate and engage with the microbial sublime via their optical senses, designers could explore alternative ways to mark, translate, and/or magnify displays towards its customization for the visually-impaired and/or the elderly members of society. Certain colour changes in microbial growth for example, could be marked (level 2) accordingly for better distinction, whilst translating (level 4) microbial livingness in the form of tactile feedback, may also help those with sight and hearing disadvantages. Meanwhile, for children's educational tools involving microorganism's growth and movement as a reward for learning; designers could introduce forms of nudging (level 5) to speed up or make more prominent the living displays, to cater for different learning speeds and/or to address neurodiversity amongst the users. Choice and diversity is important, both for those who design and the designed. Living artefacts are no different. Navigating across the taxonomy, we invite designers and users of living artefacts to become better aware of, and to position themselves from, a systematic vantage point, in the creation and engagement with living displays of the microbial world.

In terms of its adaptability, the proposed mechanisms of the taxonomy have been carefully chosen for their tunability, and proposed as adjustable mechanisms. But what does equipping designers with a set of adaptable livingness-surfacing mechanisms mean for HCI and biodesign? From our analysis of existing works in biological-HCI, we argue that it is about being able to integrate, to tune, and to manage the values of different stakeholders of living artefacts. From our case study of Flavobacteria for example (in particular, concept 2), we illustrated how increasing magnification levels can change the temporality of the potential human-flavobacteria interactions. Thus, shifting expectations in terms of how such encounters are and should be experienced; from an ambient domestic display, to a dynamic, responsive, and mutually beneficial public installation for both the humans and microbes. Similarly, translating through digitization for example, offers flexibility of computer programming to customize the qualities of livingness displays and their implicated values. Designers of *Nukabot* [20] explained how translating bacterial activity into human voice required careful tuning of its frequency (ibid., p.4), to tug at the heart of the bio-robot's carers, in triggering adequate levels of empathy and actions from them. Such levels of adaptability of the taxonomy in terms of its mechanisms therefore, are integral towards meeting the sensitivities of the microbes under exploration.

Moving forward, we remind ourselves of the fact that working with microbes by its nature is about fine tuning and fine margins between being in focus and out of focus, of contamination and sterility, to further argue for the advantages of equipping designers with adjustable mechanisms with which to attend to microbes with enhanced nuance and sensitivity.

7.2 Taxonomy Towards Noticing Microbes Well

Historically in HCI, our microbial collaborators have been positioned as an interactive material with computational and interfacing capabilities. They are regarded as ubiquitous living *things* (in contrast to living *beings*, like animals) that could be harnessed to meet certain human needs. Given such characterisation, it is not difficult to see that the current corpus of HCI research, bar a few recent exceptions (e.g., [3, 20, 48, 89, 105], etc.), places microbes' functionalities above their survivability at the centre of their analyses. What emerges is a culture of technologically-mediated, and predominantly *quantitative* noticing of microbes: How much (how fast, how closely, or how diversely) can we sense them? In contrast, less explored is the question of how well we should notice them, i.e., on how we can become more sensitive to microbes' needs.

Similarly, further consideration is needed, on the designerly ways in which we could facilitate microbes for *them* to communicate to *us*, as a part of bidirectional relationship of (often mutualistic) care giving and receiving between humans and microbes. In the macrobe world - for example in plants and animals - often show their state of wellbeing that are relatively easy to see and interpret (e.g., flowers may wilt or bloom), whilst it may not be so obvious in the microbe world.

Moving forward, we suggest that the taxonomy of microbial displays can be a framework to help designers to develop displays for people to become aware of microbes in a way that we can better understand microbes' state of wellbeing, and for people to become proficient in actioning appropriate and timely care for the organisms. Taking livingness that surfaces from *growth* as a visual marker for microbes' welfare for instance, the displays could be carefully crafted to indicate the *polarity* and *intensity* of their growth, informing the observer whether the organism is struggling or thriving (or neutral), as well as the amount of care action that is needed. Focusing on visual aesthetics and their delivery (execution) alone, via levels of visual marking (level 2) and translating (level 4) in particular, would be a feasible starting point. And to achieve such types of display would not only need technical skills but also certain degree of artistry and interpretations on the effects of the display. This is because the displays would need to have an emotive pull that is needed to encourage people into action.

As such, these types of displays invite potential collaborators from multiple disciplines, to ensure that the quality of their crafted and/or curated displays are sufficient for microbial care, on the following levels: *Technical* quality (how visually clear is the display in depicting microbial growth); *Functional* quality (how faithful is the display in conveying microbial growth); *Semantic* quality (how meaningful is the display in communicating microbes' particular needs); and *Persuasive* quality (how compelling is the display, in emotionally appealing to the viewer to act).

7.3 Reflections and Further Work

Whilst we acknowledge the multi-sensorial ways in which humans notice things, this paper have leaned heavily on one mode of human sensing for the development of our taxonomy outline (i.e., human sight/vision). We feel that it has been a necessary reduction to at least begin the much-needed conversations in the complex arts of microbial noticing, collaboration, and caring; a relatable and an accessible level of entry for diverse communities to engage with, and to discuss. That said, however, further work is needed to contextualize other forms of human sensing (e.g., smell and taste) to explore how the taxonomy could be best utilized for such scenarios.

As we further reflect on the taxonomy creation and development, an aspect that needs further clarification from the taxonomy is what we might call "Level 0", that would involve no form of proactive and tangible human intervention; towards framing the habitat as characterized by canvassing in level 1, and for living artefacts more generally. We recognize that the notion of canvassing can be inherently human-centric, framing backgrounds and assigning borders that would limit movement and interactions between microbes and the non-microbe.

Much can be learned from previous works in sustainable HCI. In Liu et al.'s work [89], for example, the authors discussed the notion of human de-centering as bringing humans *to* the organism (fungi), exploring their natural open environments, in parallel to the concept of *Earth as a Lab* ([90], p.9). Through acts of translating and noticing mycelium presence in an open forest, the researchers have argued, provided opportunities to sense and to notice other organisms that depend on the fungi too, inviting a holistic understanding of the microbe as part of a wider ecological assemblage: *"Fungi also function as bio-indicators in the sense that the health of fungi can tell us about the health of a multitude of other species. By designing tools to expand our human abilities to be able to notice these connections, we hope to gain deeper insight and perspective on how we affect and are affected by other organisms"* (p.4).

That said, we found that assigning an appropriate category and characteristics for the open space livingness displays has been challenging; limited not only by the lack of case studies that consider the open and wild environments as a microbial living artefact, but also by the absence of discussions and reflections amongst HCI communities, in naming and positioning such category in the context of HCI and interaction design. It is a direction that we aim to revisit, as a part of our ongoing process of refining and expanding the taxonomy. In doing so, we hope to contribute to the ongoing conversations in HCI, of noticing as design practice more generally (e.g., [91, 92]), and also in terms of addressing the challenges of the anthropocene age (e.g., [88]); as a part of a timely reminder and a much needed space for biological-HCI to recognize and to notice microbes in fostering a sustainable relationship between human and the non-human (microbial) stakeholders of our planet.

8 CONCLUSION

With the ever growing awareness on the significance of microbes to our ecosystems and our planet, we acknowledge the recent proliferation and diversification of microbe-based living artefact explorations in HCI, and the overall lack of existing microbe-sensitive design tools in their support. Through systematically reviewing microbial living artefacts and a case study on Flavobacteria, we have developed and instantiated a *Taxonomy of Surfacing Livingness in Microbial Displays*. Consisting of six microbe-sensitive mechanisms; 1) *Canvassing*, 2) *Marking*, 3) *Magnifying*, 4) *Translating*, 5) *Nudging*, and 6) *Molecular Programming*, the taxonomy invites designers to strategize ways of surfacing microbial livingness; a material quality inherent in living artefacts fundamental not only for their functioning, but also towards enriching how we could notice, interact, and empathize with the seemingly elusive worlds of microorganisms.

Through the taxonomy, we have provided a set of tuneable lenses for biodesigners to explore a range of possible alternatives and non-anthropocentric framing of microbial displays; towards overcoming possible surfacing constraints inherent in microbes, and also for the adaption towards integrating the diversifying values of different stakeholders of living artefacts.

ACKNOWLEDGMENTS

This work was partly supported by the *NextSkins* project, funded by the European Union's Horizon Europe research and innovation programme under grant agreement number 101071159. We thank members of Materials Experience Lab, Department of Sustainable Design Engineering, Delft University of Technology, for their feedback and support.

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A APPENDIX

Table 6: List of living artefacts analysed for taxonomy development

Number	Year	Lead Author/Artist/Designer	Artefact Name/Title	Reference
1	2008	Cheok	Empathetic Living Media	[21]
2	2011	Easterly	Tardigotchi	[29]
3	2011	Munnick	Microscopic Opera	[99]
4	2011	Riedel-Kruse	POND PONG	[116]
5	2011	Riedel-Kruse	Prisoner’s Smellemma	[116]
6	2012	Cinti	Living Mirror	[22]
7	2013	Braund	Slime Mould Music	[12]
8	2013	Czjek	Anima	[25]
9	2013	Hosseini	Bacterium and Scientific Visualization	[60]
10	2013	Kuznetsov	Living Sensing Systems	[78]
11	2013	Parkes	Algae Prototype	[111]
12	2015	Braund	BioComputer Music	[13]
13	2015	Hossain	Interactive Cloud Experimentation	[59]
14	2015	Lee	Trap it!	[87]
15	2015	van Eck	Biological Content Generation	[30]
16	2016	Gerber	BioGraphr	[39]
17	2016	Henriques	Caraval	[55]
18	2017	Hamidi	Rafigh	[49]
19	2017	Kim	Reviving Drachma	[69]
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