FlavoMetrics: Towards a Digital Tool to Understand and Tune Living Aesthetics of Flavobacteria

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

Jose F. Martinez Castro
Delft University of Technology
Delft, the Netherlands
j.f.martinezcastro@tudelft.nl

Pascal Barla
Inria
Bourdeaux, France
pascal.barla@labri.fr

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

Abstract
Integrating microorganisms into artefacts is a growing area of interest for HCI designers. However, the time, resources, and knowledge required to understand complex microbial behaviour limits designers from creatively exploring temporal expressions in living artefacts, i.e., living aesthetics. Bridging biodesign and computer graphics, we developed FlavoMetrics, an interactive digital tool that supports biodesigners in exploring Flavobacteria's living aesthetics. This open-source tool enables designers to virtually inoculate bacteria and manipulate stimuli to tune Flavobacteria's living colour in a digital environment. Six biodesigners evaluated the tool and reflected on its implications for their practices, for example, in (1) understanding spatio-temporal qualities of microorganisms beyond 2D, (2) biodesign education, and (3) the experience prototyping of living artefacts. With FlavoMetrics, we hope to inspire novel HCI tools for accessible and time- and resource-efficient biodesign as well as for better alignment with divergent microbial temporalities in living with living artefacts.

Authors Keywords
Biodesign; living colour interfaces; living aesthetics; temporality; design tools; computer graphics.

CSS Concepts
- Human-centered computing → Interactive systems and tools

DIS '23, July 10–14, 2023, Pittsburgh, PA, USA

ACM ISBN 978-1-4503-9893-0/23/07.
https://doi.org/10.1145/3563657.3596085

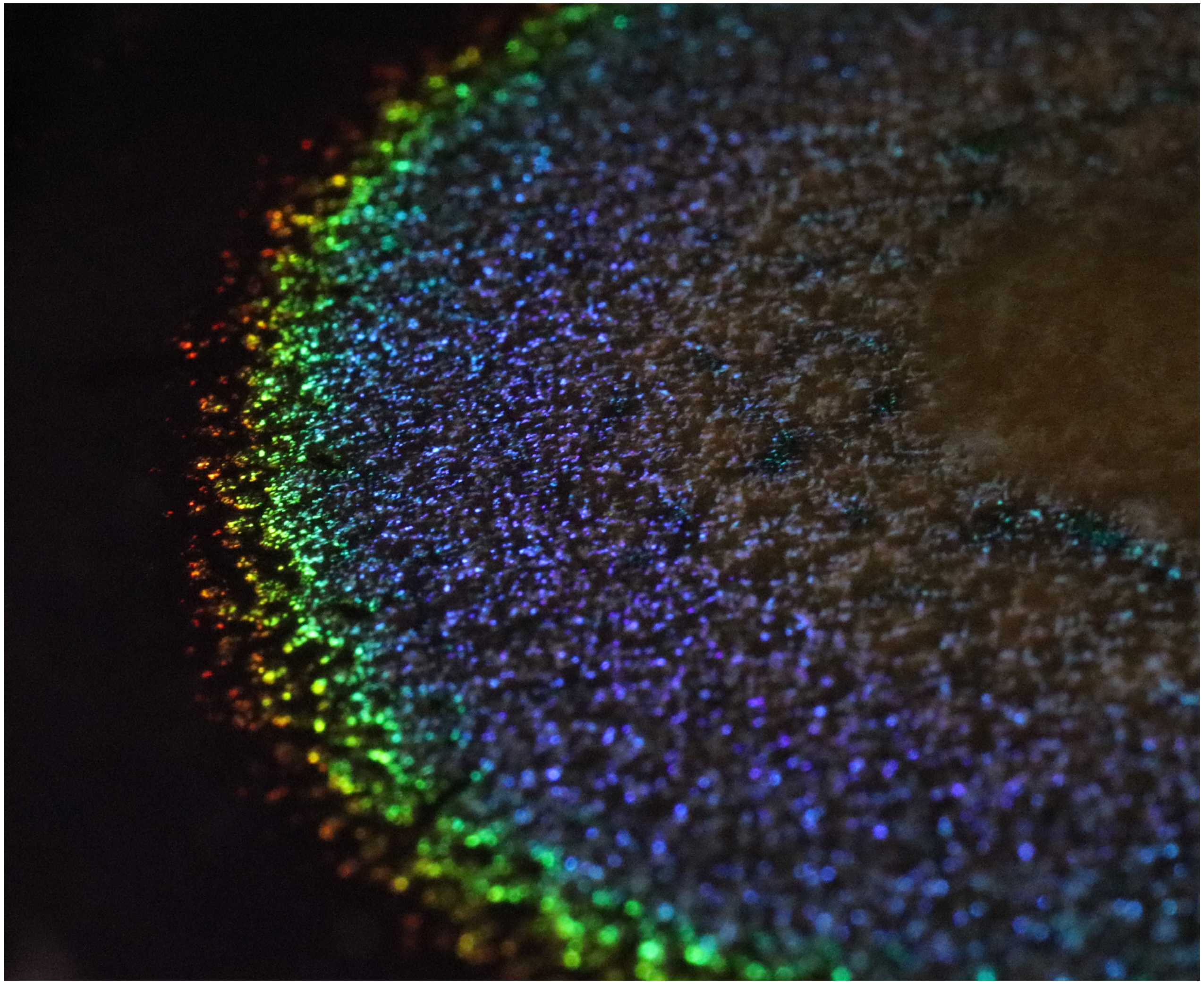
INTRODUCTION

There is a growing interest among design and HCI communities in integrating living organisms into artefacts as interactive design elements [27, 34, 36]. In these living artefacts, microorganisms, such as algae [9, 35], bacteria [6, 20], and fungi [15, 22], offer unique responsive behaviours to achieve novel functions, expressions, and interaction possibilities.

Common to all, the unique temporal qualities of living microorganisms are embraced as design potentials [27]. In more recent works in biodesign, scholars have explored the complex behaviour and expression of microorganisms, for example, how Flavobacteria's living colour can be tuned with humidity [20] or how diverse kinetic stimuli affect the living light output of bioluminescent algae [9]. These explorations emphasise the role of understanding living aesthetics (i.e., the way humans experience qualities of livingness in living artefacts [27]), not only as a way to design unique expressions and functions but also to surface livingness for empathy [16] and timely noticing of microorganism's struggles [29], towards reciprocal relationships with living artefacts [27]. However, understanding the temporal behaviour of living organisms remains a challenge in biodesign [9, 27, 35]. It requires time, resources, and knowledge, as:

- Organisms have different circadian rhythms and growth rates (e.g., the stationery and decline/death phases are different for all organisms [31]). It might take days or weeks to observe changes in microorganisms;
- Unique growing conditions, equipment, and sterility are needed;
- Stabilising conditions and exploring the effect of one stimuli at a time is needed for understanding the input and output relations. This requires multiple experiments that might take weeks (if not months) to complete.

Novel design tools are needed to mitigate these challenges in biodesign in understanding potential expressions of living organisms. To that aim, this pictorial presents an interactive digital tool, FlavoMetrics, to understand and model the temporal qualities of a specific organism, namely Flavobacteria. We explored the applicability and implications of our tool with a user study inviting six biodesigners.



RELATED WORK

Digital Tools to Understand and Model Living Media

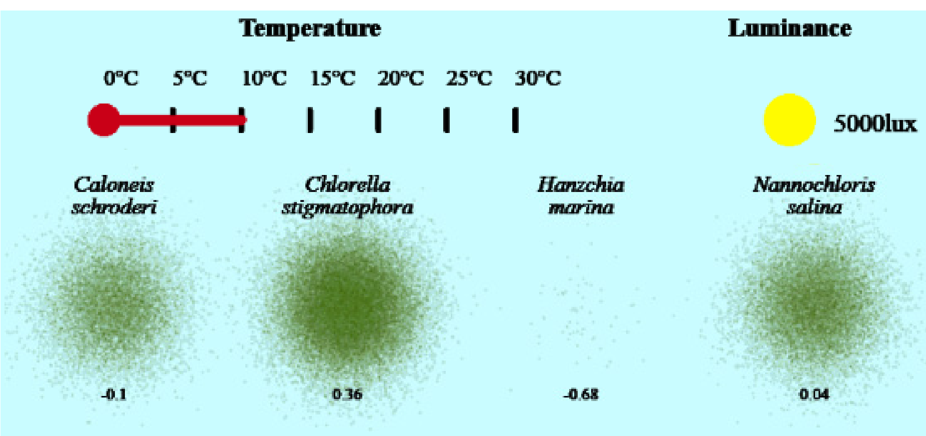
Over the last decades, many digital tools have been proposed within the HCI community to support the understanding of the temporal behaviour of diverse media (e.g., for shape-changing materials [40], textiles [13], textile weaving [33]). Considering the similarities between such alive-like materials and living media, these tools serve as valuable examples while addressing the call for novel tools in the nascent field of biodesign.

Zhou et al. [42] presented an overview of digital tools used in the design of living artefacts, which aim to support biodesigners in understanding, embodying, or perpetuating the habitats where living artefacts are situated. An example is a solar radiation analysis to find the optimum form of a living artefact, taking into account the environment, desired expressions, and organisms' needs [3]. Other examples include digital tools to predict pattern formation in bacterial colonies [7, 39]. In line with this, simulations are used for bioluminescence in micro-architectures [41] and wearables from bacterial cellulose [2]. Yet, such tools do not allow for creatively exploring the possible temporal expressions of living artefacts.

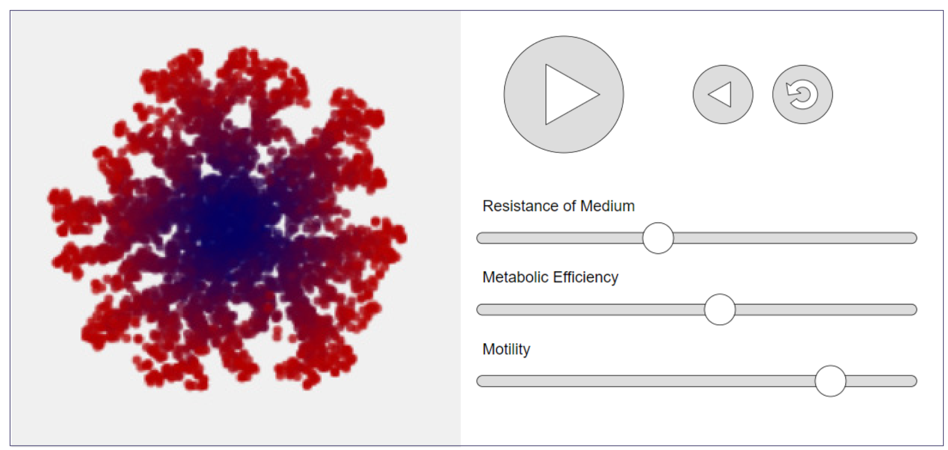
In biology and bioengineering, we see various computer-aided design (CAD) tools [19, 32] that model microorganisms to accelerate robust engineering of biological systems while reducing experimental testing. Accessible, interactive tools are presented in projects such as Scott's World [5] and Algae Growth Simulation [38] in which users can tune organisms' behaviour (e.g., motility) or their environment (e.g., temperature). While these tools show organisms' growth and responsive behaviour in an agile manner, they lack the possibility for design intervention (e.g., how living aesthetics might change with the ways in which we inoculate living media) and visual likeness to the real organism, which is crucial for exploring their complex living aesthetics in biodesign.

Conveying Living Aesthetics through Computer Graphics

Computer graphics can enhance the likeness to the real world organism by providing improved visual quality through both real world data and computer generated textures. Sage Jenson's [25] simulations of biological complex systems bring about many of the living aesthetics of microorganisms through high-end visualisation and simulations using algorithms based on real world data. Other 3D artists have also showcased methods to produce realistic and convincing interactive visuals of biological and temporal phenomena using procedural modelling (e.g., for bacterial colonies [23], cobwebs [14], rusting metal [30]). Through combining real world data of the organism with procedural computer graphics, a convincing simulation of an organism's temporal and responsive behaviour can be created, showcasing its living aesthetics in digital media.



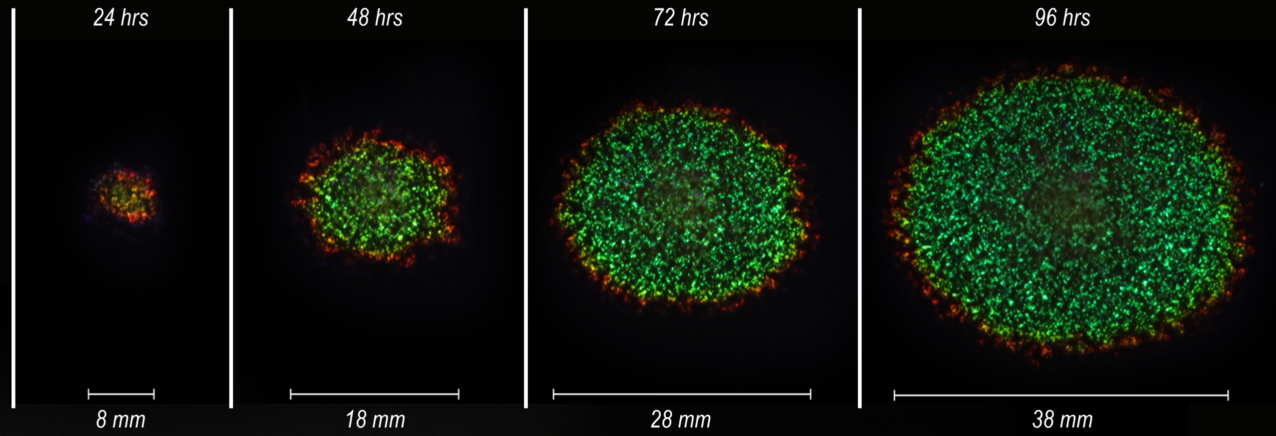
Algae Growth Simulation ©Tyler Sloan [38]

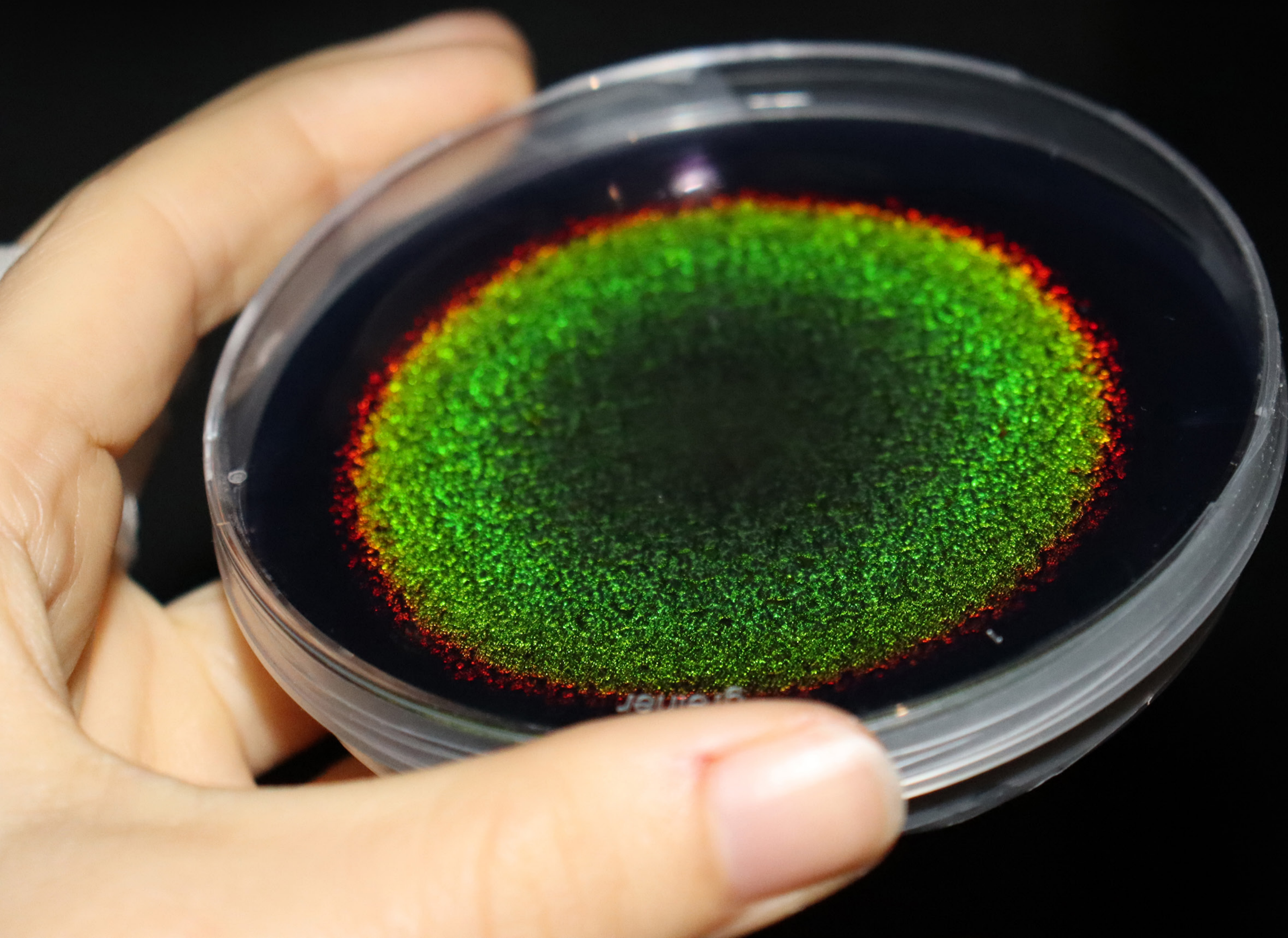


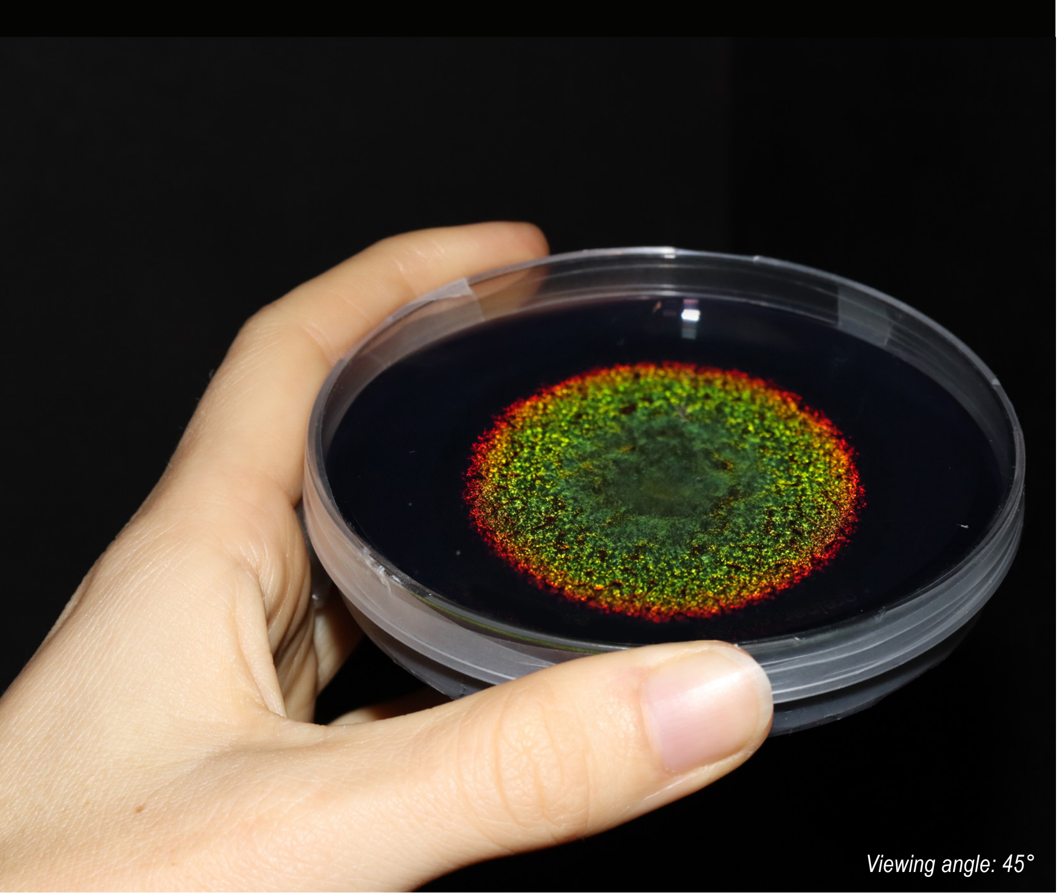
Scott's World - Microbial Pattern Formation ©Dirk Brockmann [5]

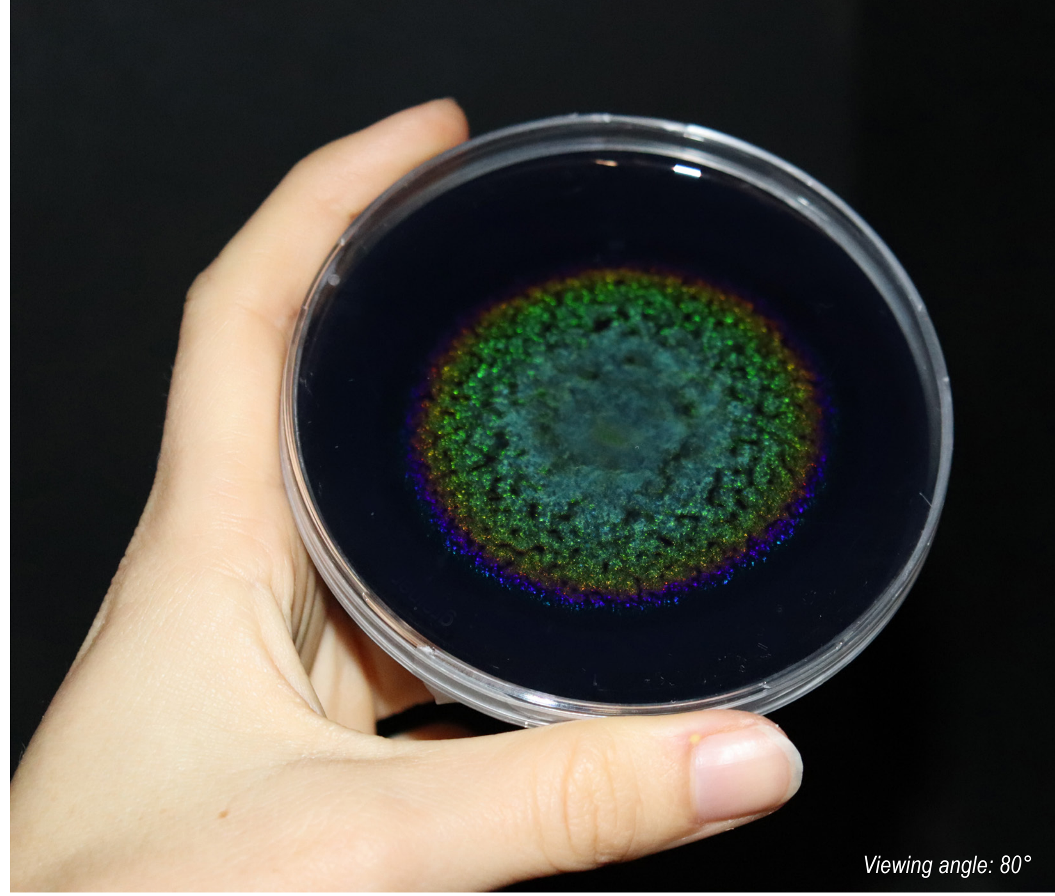
Flavobacteria's Growth over Four Days

A colony of Flavobacteria increases in size over time and displays a wide variety of colours, ranging from violet and red to more dominant green hues.









FLAVOMETRICS

In an attempt to bridge the gap in exploring living aesthetics in biodesign in an agile yet realistic manner, we developed a digital tool for a specific organism, namely Flavobacteria. Within our multidisciplinary team, we first simulated their iridescence by capturing and translating visual data. From here, we developed an interactive tool, FlavoMetrics, which aims to support biodesigners in performing quick design explorations with Flavobacteria. In this chapter, we elaborate on the development of the tool (further details can be found in the supplements). FlavoMetrics' open-source project can be found here.

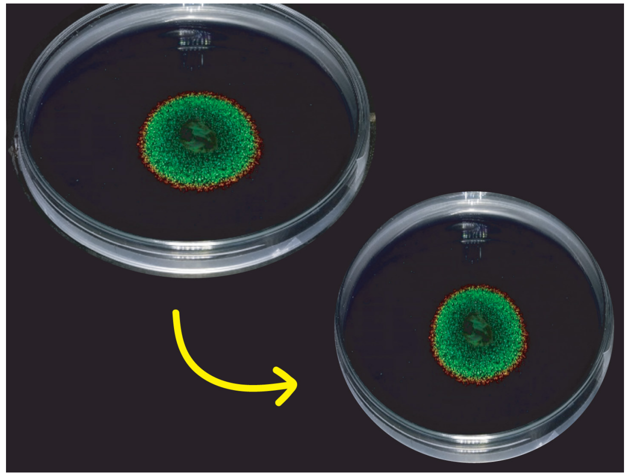
Challenges of Flavobacteria

Flavobacteria were recently introduced to HCI designers as a living medium [20] due to the potential they offer through their vivid, iridescent colourations when grown on a solid surface. This angle-dependent optical effect is a result of their cell organisation into photonic crystals, which interact with light [26, 28, 37]. As cells multiply, glide over the surface, and organise themselves, the colony of Flavobacteria will grow outward and change colour depending on the cells' age, density, and arrangement. Their living aesthetics, concerning changes in form, texture, and iridescent colour, are affected by, for instance, various environmental factors (e.g., humidity) and the inoculation technique (i.e., method of applying bacteria to a surface), as shown by [20]. While this iridescence, temporality, and responsiveness emphasise Flavobacteria's potential as an attractive living medium, the complex combination of spatial and temporal qualities poses a challenge for understanding and predicting Flavobacteria's living aesthetics. Models in computer graphics have shown the possibilities of rendering various iridescent effects [21, 10], yet more complex effects such as those of Flavobacteria's photonic crystals require data-driven approaches as described in this work.

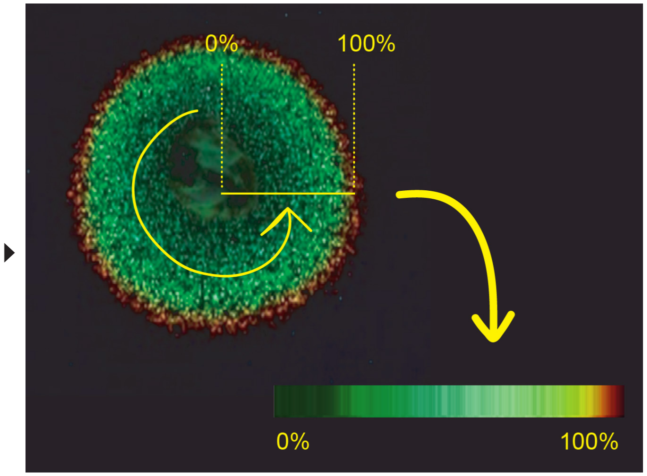
Collecting Data on Flavobacteria's Iridescence

We used a custom-made tool (based on [20]) to automatically capture the full colour range (72 angle configurations) of a 5-day-old Flavobacteria colony. The images were translated through a Python script into linear colour gradients by merging the radial colour gradients across the colony. These colour gradients were then translated into bidirectional reflectance distribution function (BRDF) maps, which define how surfaces reflect light based on incoming lighting and viewing directions and are commonly used in the field of computer graphics. Each BRDF map relates to the colour of cells as a function of distance from the centre (inoculation point) of the colony for a specific light/view configuration. When implemented in material rendering software such as Blender 3D, the colour can be accessed from the BRDF map as a function of the camera view and light directions.

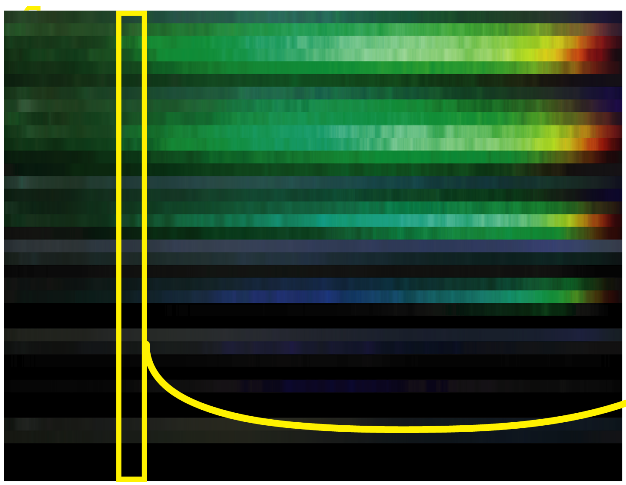
Capture tool to collect images of Flavobacteria [20]



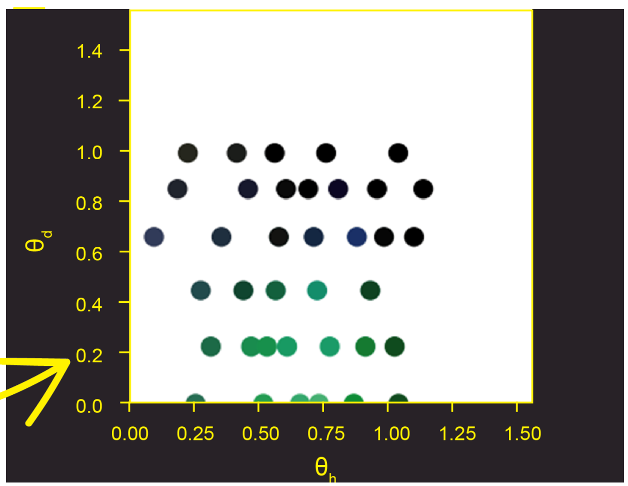
Perspective transformation of images



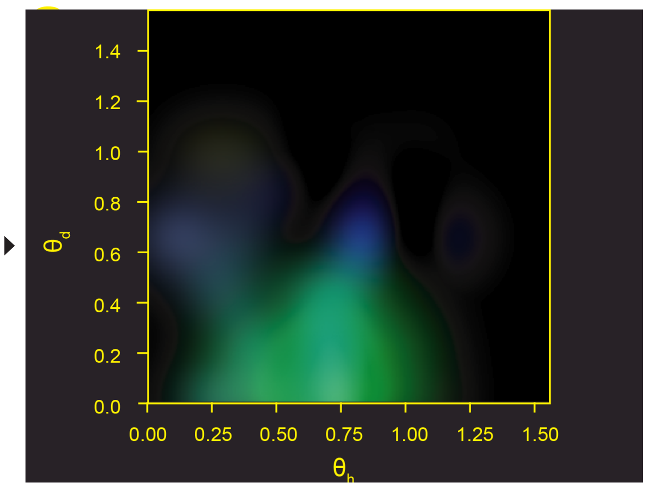
Fusion of radial colour gradients



List of representative colour gradients for different angle configurations



BRDF map from colour values of a single location



Interpolation of data per BRDF map

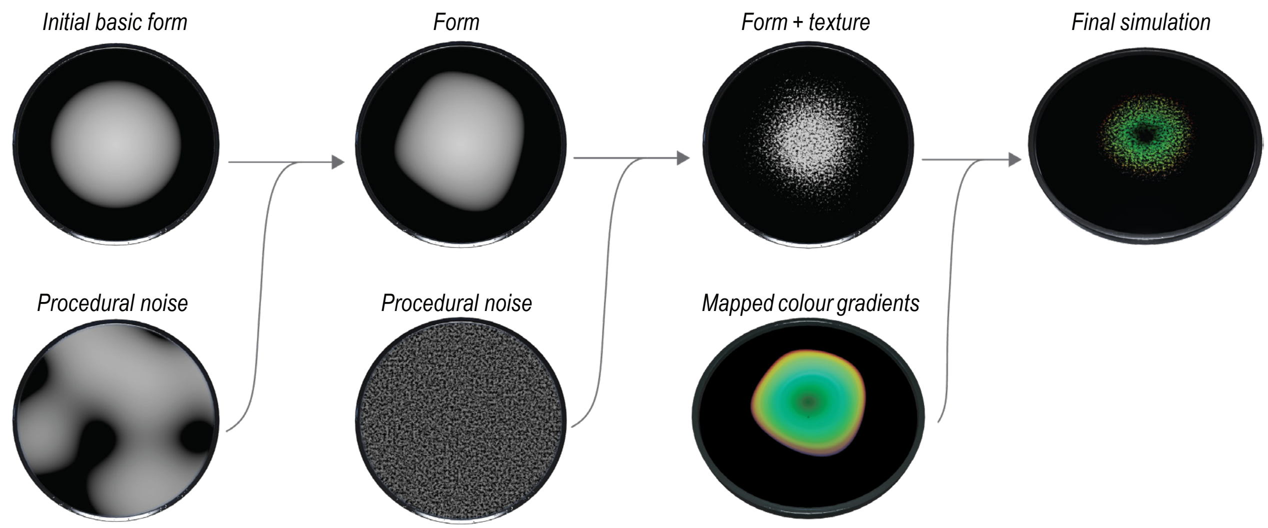
Translating Data into a Procedural Texture

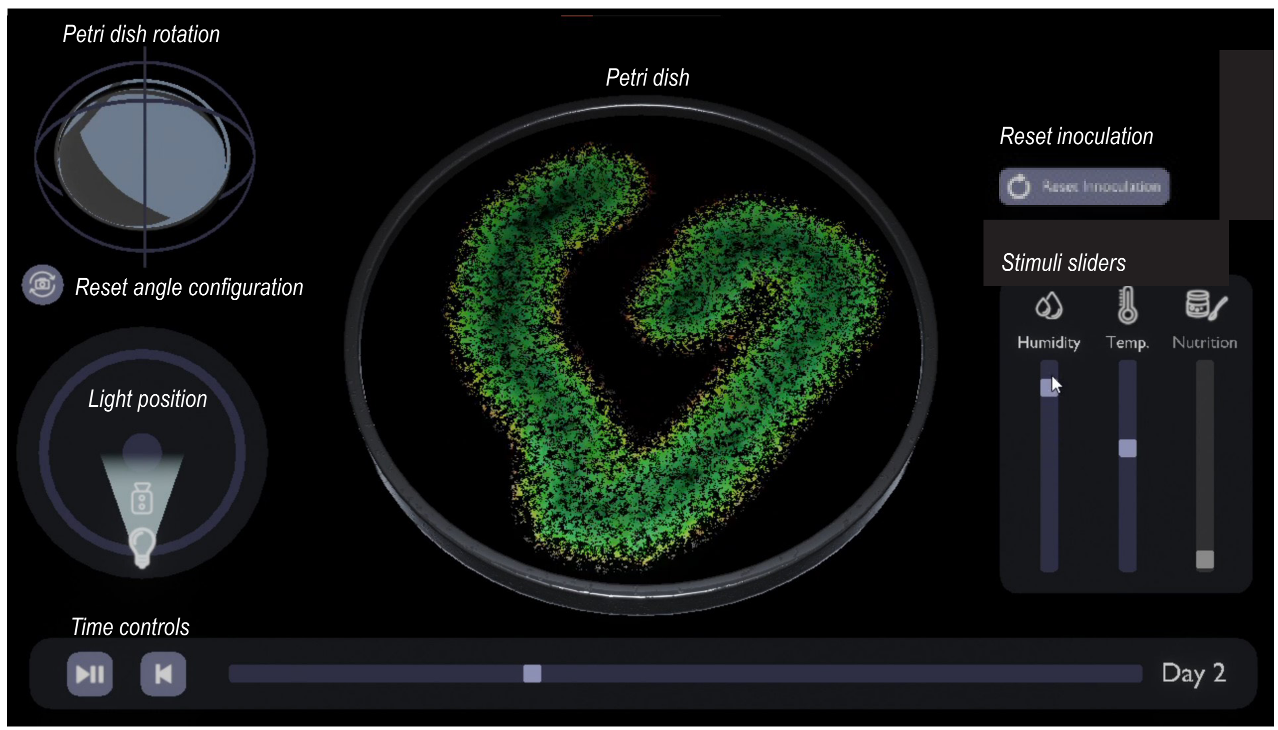
In order to simulate the changes in form and texture of Flavobacteria, we developed a procedural texture of the bacteria colony from the captured images. In computer graphics, a procedural texture is a texture that is created using mathematical descriptions rather than directly stored data. We then embedded the colours from the BRDF map on the procedural texture to create the final simulation of the Flavobacteria colony. The figure on the right shows the multiple layers involved in the development of the procedural texture.

This procedure allows for full control over the appearance of the colony, such as shape, size, and texture. Building upon the insights on how Flavobacteria's living aesthetics can be tuned with humidity [20], we manually mapped these parameters to growth (# of days) and humidity levels. Due to the procedural texture and BRDF maps, the tool can visually estimate Flavobacteria's growth, filling in the gaps of how the living aesthetics were developing in-between the capture moments, which was highlighted as one of the limitations in previous work by Groutars and Risseeuw et al. [20].

Interactive Tool

In order to engage biodesigners in a conversation about future digital tools for biodesign, we developed an interactive tool from the simulation using the Blender Game Engine (UPBGE). The simulation was enhanced with an interactive inoculation feature allowing the user to freely inoculate the bacteria anywhere on the digital Petri dish, which is then set as the origin point of the bacteria's growth. This implementation helps the user of the tool envision how their interventions affect the growth of Flavobacteria. Finally, a graphical user interface (GUI) was developed for the tool, adding accessible control over the parameters, including time, light position, Petri dish rotation, and environmental conditions, to enable the user to explore the temporality and responsiveness of living media.





A STUDY WITH BIODESIGNERS

We conducted a study with six biodesigners to evaluate FlavoMetrics and reflect on how such interactive digital tools could support the design process with diverse living media.

Set-up

FlavoMetrics was displayed on an iPad, allowing the participants to interact with a pencil or directly with touch. To introduce the participants to Flavobacteria and enable them to compare the simulation to the real organism, we placed a sample of Flavobacteria on the same table as well as a desk light resembling the tool's interactive light. Through observing such a "static" sample, participants would become aware that temporal changes in Flavobacteria's expressions are not directly noticeable to the human eye [29]. For our analysis, we made a voice recording as well as a screen recording of the user interface.

Participants

We invited six biodesigners, including two artists, three design researchers, and a landscape designer. We chose biodesigners from both academia and design practice to uncover more possibilities of digital tools for biodesign, which we expected might differ based on the focus of the biodesign practice. The participants had 3-8 years of experience in biodesign, collaborating with diverse microorganisms, including cyanobacteria, algae, and fungi. One of the participants also had experience designing with Flavobacteria.

Procedure

The study began by introducing participants to Flavobacteria's iridescent and temporal qualities by presenting the sample and simulation. After a demonstration on how the GUI allows one to observe and tune living aesthetics, participants were given time to freely explore the tool while thinking-aloud. Each session took about an hour, and was completed with an interview, discussing their experience of using the interactive tool and reflecting on how such a tool could support them in their own biodesign practice.

Results

The answers of the biodesigners showed great variation in the ways in which they imagined using similar digital tools in their own practice. Overall, the participants saw great value in interactive simulations of living organisms and all agreed to the positive implications of FlavoMetrics, including how it allows you to quickly cycle through design explorations for living aesthetics and its potential to save resources in a biolab.

As expected, the implications highlighted by biodesigners were influenced by the focus of the biodesigners' practice. For example, the landscape designer wanted to simulate living media on a 3D formed facade, while two design researchers with teaching experience mentioned how students could benefit from the tool. Likewise, another design researcher felt the tool would restrict creativity and freedom in navigating the design space, strongly pointing towards educational purposes.

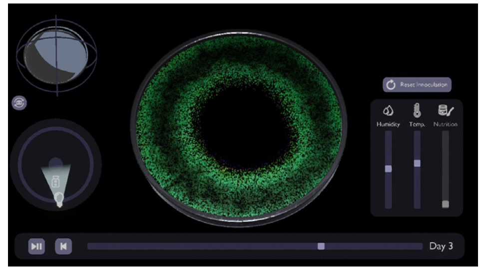
The type of microorganisms that biodesigners had experience with also influenced their experience with FlavoMetrics. For example, one biodesigner working with Cyanobacteria wished to have more control over lighting conditions, as light is crucial for the organism's growth. Another biodesigner working with Cyanobacteria had a hard time imagining using the tool in their own project as this microorganism is not as expressive in colour as Flavobacteria. Nevertheless, such organisms could express their wellbeing in simulations through other types of change (e.g., form).

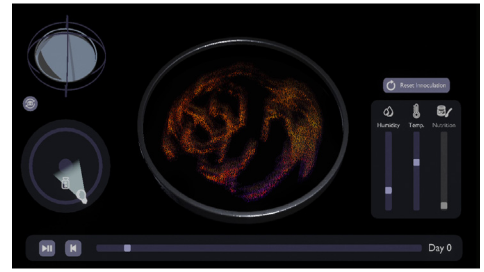
The expert on Flavobacteria especially valued the inoculation feature, through which you can quickly iterate between different patterns. Yet, they stated the tool would be more interesting for designers who are not yet familiar with Flavobacteria's living aesthetics, as an expert might already anticipate the majority of the design outcomes.

Finally, two participants stated that one could not really explore unknown relations between input and output with FlavoMetrics unless it could predict the behaviour of microbes.

From our study, we identified directions for future digital tools to support the design of living artefacts.

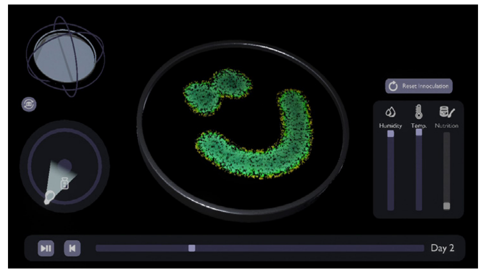
"Probably all the work I can do in one month can be compacted into one day."

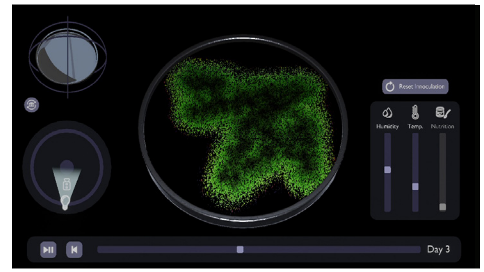




"It might be useful to compare user interactions that happen on a completely digital level and experiences of the real thing."

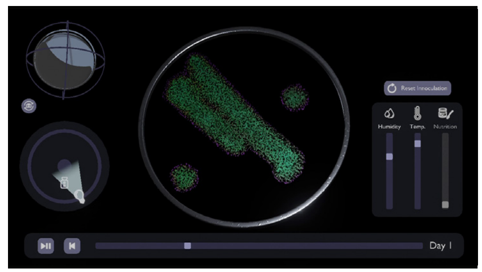
"I would love to have this for Cyanobacteria, so I can play around with different patterns, shapes of agar, etcetera"

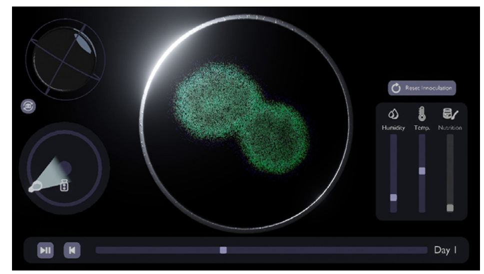




"I'd be really interested to load in a 3D file and predict growth. You could make a nice render of it and export it with a spec sheet."

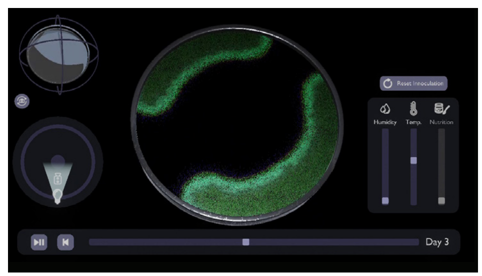
"I really enjoy that you can draw with it and see different patterns."

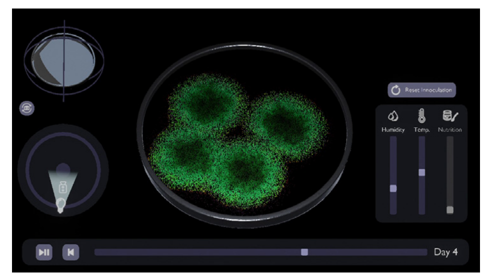




"I want to see how they crash into each other."

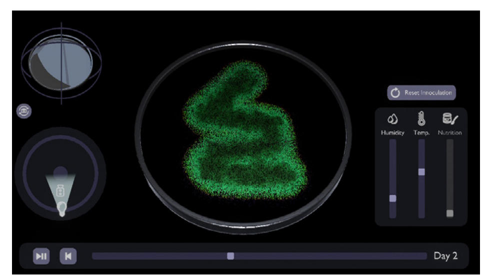
"I have seen similar tools used in microbiology education but they provide not as high fidelity as this one."





"For me as a designer, it helps if it becomes visual. It's still not the real thing ofcourse, but it's much more tangible than reading about it."

"You can see their iridescence very well, nicely done. Especially this subtle blue. Only at specific angles, but that is also the case with Flavo."

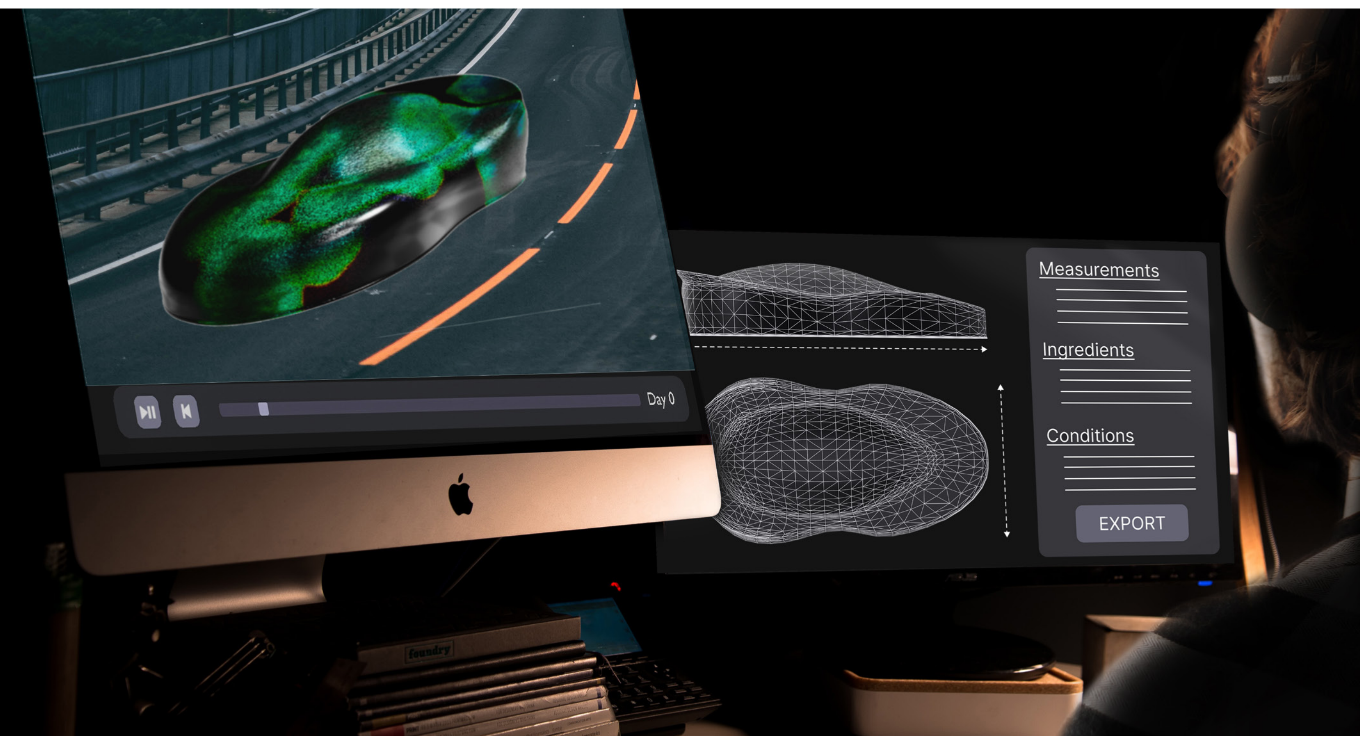


"It can be used as an introduction in design education, or for kids. Or, during a pandemic, when you don't have access to a lab."

BIODESIGN IMPLICATIONS

Developing FlavoMetrics, we aimed to create a potential tool that could support biodesigners in navigating the design space of living aesthetics. The implications of FlavoMetrics that resulted from our user study were in line with these expectations. To facilitate the intended use, the tool can be further developed by including more stimuli to support biodesigners in tinkering with Flavobacteria, allowing them to explore living aesthetics in relation to various input mechanisms.

Besides, new implications were discovered that focused on understanding spatio-temporal qualities beyond 2D, biodesign education, and experience prototyping of living artefacts in biodesign. In this section, we elaborate on these implications of FlavoMetrics with diverse scenarios, specifying the required modifications to the tool's working principle and GUI.



Understanding Spatio-Temporal Qualities Beyond 2D with FlavoMetrics

The tool can be used to envision how Flavobacteria grow and behave on complex shapes with different scales beyond 2D Petri dishes, enabling designers to get a better understanding of Flavobacteria's spatio-temporal qualities. To that end, the tool could be further developed by allowing the import of 3D models. For example, using FlavoMetrics, one can imagine how Flavobacteria's living colour can be used as a sustainable alternative to coating for automobiles, showcasing the unique iridescence of these microorganisms through a complex 3D form.

Biodesign Education with FlavoMetrics

FlavoMetrics can be used as a didactic tool to introduce Flavobacteria to designers. This would make biodesign more accessible, similar to, for example, affordable DIY-bio tools (e.g., [18]) and Hoissain et al.'s [24] cloud experimentation architecture. In addition, FlavoMetrics provides a digital environment for more time- and resource efficient biodesign education. Designers who are novices at working with Flavobacteria can learn the basics of the microorganisms' behaviour in this digital learning environment, as well as use the tool as a generative tool to brainstorm on the ideas for novel interaction scenarios. The tool could be further developed by including educational content on Flavobacteria's behaviour and allowing for virtual collaborations.

Experience Prototyping with FlavoMetrics

FlavoMetrics can support biodesigners in conducting experiential characterization studies with living artefacts (8, 11, 12, 17). With such a tool, researchers can communicate how the living artefact changes over time and what it could be like for users to interact with a living artefact through the digital representation of the artefact in context. This can mitigate some of the challenges in conducting user studies with living organisms, such as the approval of ethic committees (for biosafety) and communicating the slow changes in the living artefacts due to, for example, environmental stimuli. For this, the tool could be further developed to enable participants to digitally interact with such artefacts and reflect on its potential implications. Long term use scenarios in realistic contexts can be integrated into such tools to trigger further discussions on the implications of such artefacts in the everyday. Additionally, AR/VR technologies could be explored to enhance the interactive experience with the digital twin.

REFLECTIONS AND FUTURE WORK

In this pictorial, we presented FlavoMetrics, a digital tool that enables biodesigners to virtually explore the living aesthetics of Flavobacteria. Through discussions with biodesigners working with diverse living media, we identified how such an interactive tool can assist in navigating the design space of living aesthetics through: understanding spatio-temporal qualities beyond 2D, biodesign education, and experience prototyping of living artefacts. In future work, we would like to delve further into the implications by conducting in-situ user studies with biodesigners to reflect on the long-term use and benefits of our tool.

Although we aim to inspire digital tools to aid biodesigners in exploring living microorganisms' temporality and responsiveness in an agile, accessible, and resource-efficient manner, we do not suggest that they should replace experiments in a tangible lab environment. Instead, we envision a way of blended learning [4], combining digital and physical experiments. Such hands-on practice is essential for biodesigners to get a feel for the organisms' temporality and behaviour and a sense of empathy towards living organisms [16], towards more microbe-sensitive [29] biodesign practices. Additionally, novel expressions might still reveal themselves in tangible experiments due to unforeseen conditions and the microorganisms' agency, which cannot be captured in digital tools.

We designed FlavoMetrics specifically for Flavobacteria. Nevertheless, we hope that these implications can inspire multidisciplinary collaborations in developing digital tools for various kinds of microorganisms. Here, we envision digital tools being adapted to the unique temporalities and needs of other microorganisms, for example, by allowing interactions with microorganisms in liquid medium or tuning other habitat conditions such as light intensity.

Even though we intended FlavoMetrics to be used in the design time of living artefacts, we envisage the potential use of such tools in living with microbe-embedded living artefacts. By translating complex microbial behaviour and invisible metabolic activities to humans through digital systems (e.g., [1]), we can help attune to microbes' time to establish timely care practices and elicit unique interactions and experiences toward reciprocal and evolving relationships with living artefacts. We aim to elaborate on this potential of FlavoMetrics in our future work.

ACKNOWLEDGMENTS

We thank members of Materials Experience Lab at Delft University of Technology for their feedback and support. Special thanks to Prof. Dr. Baris Surucu from Middle East Technical University for inspiring the name of our tool.

REFERENCES

[1] Rachel Armstrong. (2022) Biodesign for a culture of life: Of microbes, ethics, and design, in Lockton, D., Lenzi, S., Hekkert, P., Oak, A., Sádaba, J., Lloyd, P. (eds.), DRS2022: Bilbao, 25 June - 3 July, Bilbao, Spain. https://doi.org/10.21606/drs.2022.144

[2] Augmented Architectures. 2018. Embryonic Spaces. [Video file]. Available at: https://vimeo.com/185173399?embedded=true&source=vimeo_logo&owner=45986959

[3] BigRep. 2019. The GENESIS Eco Screen – How BigRep Is Making Cities Greener With 3D Printed Urban Ecosystems. BigRep. https://bigrep.com/posts/genesis-eco-screen/

[4] Curtis J. Bonk and Charles R. Graham. (2004). Handbook of blended learning: Global Perspectives, local designs. San Francisco, CA: Pfeiffer Publishing.

[5] Dirk Brockmann. (2018). Scott's World*. Available at: https://www.complexity-explorables.org/explorables/scotts-world/

[6] Mirela Alistar and Margherita Pevere. 2020. Semina aeternitatis: Using bacteria for tangible interaction with data. Extended Abstracts of the 2020 CHI Conference on Human Factors in Computing Systems, 1–13. https://doi.org/10.1145/3334480.3381817

[7] Christoph Bader, Sunanda Sharma, Rachel Soo Hoo Smith, Jean Disset, and Neri Oxman. 2020. Viva in silico: A position-based dynamics model for microcolony morphology simulation. ALIFE 2018 - 2018 Conference on Artificial Life: Beyond AI. https://doi.org/10.1162/isal_a_00060

[8] Bahareh Barati, Elvin Karana, and Paul Hekkert. 2019. Prototyping Materials Experience Towards a Shared Understanding of Underdeveloped Smart Material Composites. (2019).

[9] 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

[10] Laurent Belcour, and Pascal Barla. 2017. A Practical Extension to Microfacet Theory for the Modeling of Varying Iridescence. ACM Transactions on Graphics 36 (2017). Issue 4. https://doi.org/10.1145/3072959.3073620

[11] Marion Buchenau and Jane Fulton Suri. 2000. Experience Prototyping.

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

[13] Jose Francisco Martinez Castro, Alice Buso, Jun Wu, and Elvin Karana. 2022. TEX(alive): A TOOLKIT TO EXPLORE TEMPORAL EXPRESSIONS IN SHAPE-CHANGING TEXTILE INTERFACES. Designing Interactive Systems Conference, 1162–1176. https://doi.org/10.1145/3532106.3533515

[14] Hosuk Chang and David Luoh. 2019. Dust and cobwebs for Toy Story 4. ACM SIGGRAPH 2019 Talks, SIGGRAPH 2019. https://doi.org/10.1145/3306307.3328183

[15] 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

[16] 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

[17] Hazal Ertürkan, Elvin Karana, and Ruth Mugge. (2022) Is this alive? Towards a vocabulary for understanding and communicating living material experiences, in Lockton, D., Lenzi, S., Hekkert, P., Oak, A., Sádaba, J., Lloyd, P. (eds.), DRS2022: Bilbao, 25 June - 3 July, Bilbao, Spain. https://doi.org/10.21606/drs.2022.796

[18] Gilad Gome, Julian Waksberg, Andrey Grishko, Iddo Yehoshua Wald, and Oren Zuckerman. 2019. OpenLH: Open Liquid-Handling System for Creative Experimentation with Biology. In Proceedings of the Thirteenth International Conference on Tangible, Embedded, and Embodied Interaction (Tempe, Arizona, USA) (TEI '19). ACM, New York, NY, USA, 55–64. https://doi.org/10.1145/3294109.3295619

[19] Thomas E. Gorochowski, Jonathan R. Karr, Fabio Parmeggiani, and Boyan Yordanov. 2021. Editorial: Computer-Aided Biodesign Across Scales. Frontiers in Bioengineering and Biotechnology 9 (6 2021). https://doi.org/10.3389/fbioe.2021.700418

[20] 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

[21] Ibón Guillén, Julio Marco, Diego Gutierrez, Wenzel Jakob, and Adrian Jarabo. 2020. A general framework for pearlescent materials. ACM Transactions on Graphics 39 (11 2020). Issue 6. https://doi.org/10.1145/3414685.3417782

[22] 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

[23] Curtis Holt. 2022. How I Created Microbial Effects in Blender 3.0! [Video file]. Available at: https://www.youtube.com/watch?v=nup40poz4sk&ab_channel=CurtisHolt

[24] Zahid Hossain, Xiaofan Jin, Engin W. Bumbacher, Alice M. Chung, Stephen Koo, Jordan D. Shapiro, Cynthia Y. Truong, Sean Choi, Nathan D. Orloff, Paulo Blikstein, and Ingmar H. Riedel-Kruse. 2015. Interactive cloud experimentation for biology: An online education case study. Conference on Human Factors in Computing Systems - Proceedings 2015-April, 3681–3690. https://doi.org/10.1145/2702123.2702354

[25] Sage Jenson. 2019. Physarum. https://cargocollective.com/sagejenson/physarum

[26] 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

[27] 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.

[28] 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

[29] Raphael Kim, Clarice Risseeuw, Eduard Georges 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). Association for Computing Machinery, New York, NY, USA, Article 156, 1–21. https://doi.org/10.1145/3544548.3581417

[30] Ryan King. 2022. Procedural Extreme Rusty Metal (Blender Tutorial) [Video file]. Available at: https://www.youtube.com/watch?v=iaPf5GDBfTs&ab_channel=RyanKingArt

[31] Michael T. Madigan, Kelly S. Bender, Daniel H. Buckley, W. Matthew Sattley and David A. Stahl. (2019) Brock Biology of Microorganisms. New York (N.Y.), N.Y.: Pearson.

[32] Lucia Marucci, Matteo Barberis, Jonathan Karr, Oliver Ray, Paul R. Race, Miguel de Souza Andrade, Claire Grierson, Stefan Andreas Hoffmann, Sophie Landon, Elibio Rech, Joshua Rees-Garbutt, Richard Seabrook, William Shaw, and Christopher Woods. 2020. Computer-Aided Whole-Cell Design: Taking a Holistic Approach by Integrating Synthetic With Systems Biology. Frontiers in Bioengineering and Biotechnology 8 (8 2020). https://doi.org/10.3389/fbioe.2020.00942

[33] Elizabeth Meiklejohn, Felicita Devlin, John Dunnigan, Patricia Johnson, Joy Xiaoji Zhang, Steve Marschner, Brooks Hagan, and Joy Ko. 2022. Woven Behavior and Ornamentation: Simulation-Assisted Design and Application of Self-Shaping Woven Textiles. Proceedings of the ACM on Computer Graphics and Interactive Techniques 5 (9 2022). Issue 4. https://doi.org/10.1145/3533682

[34] 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

[35] 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

[36] 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

[37] 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

[38] Tyler Sloan. (2018). Algae Growth Simulation - OpenProcessing. Available at: https://www.openprocessing.org/sketch/494793/

[39] Rachel Soo Hoo Smith, Christoph Bader, Sunanda Sharma, Dominik Kolb, Tzu Chieh Tang, Ahmed Hosny, Felix Moser, James C. Weaver, Christopher A. Voigt, and Neri Oxman. 2020. Hybrid Living Materials: Digital Design and Fabrication of 3D Multimaterial Structures with Programmable Biohybrid Surfaces. Advanced Functional Materials 30 (2 2020). Issue 7. https://doi.org/10.1002/adfm.201907401

[40] Yasaman Tahouni, Isabel P.S. Qamar, and Stefanie Mueller. 2020. NURBSforms: A modular shape-changing interface for prototyping curved surfaces. TEI 2020 - Proceedings of the 14th International Conference on Tangible, Embedded, and Embodied Interaction, 403–409. https://doi.org/10.1145/3374920.3374927

[41] Guro Tyse, Martin Tamke, Mette Ramsgaard Thomsen, and Aurélie F. Mosse. 2022. Bioluminescent micro-architectures: planning design in time, an eco-metabolistic approach to biodesign. Architecture, Structures and Construction (4 2022). https://doi.org/10.1007/s44150-022-00038-9

[42] 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(2), 57-73. https://doi.org/10.57698/v16i2.05