Living light interfaces - an exploration of bioluminescence aesthetics

Barati, Bahareh; Karana, Elvin; Pont, Sylvia; Van Dortmont, Tim

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LIVING LIGHT INTERFACES —
AN EXPLORATION OF BIOLUMINESCENCE AESTHETICS

BAHAREH BARATI
Industrial Design Engineering, TU Delft
Delft, the Netherlands
Industrial Design, TU Eindhoven
Eindhoven, the Netherlands
b.barati@tue.nl

ELVIN KARANA
Industrial Design Engineering, TU Delft
Delft, the Netherlands
CARADT, Avans University of Applied Sciences
Breda, the Netherlands
e.karana@tudelft.nl

SYLVIA PONT
Industrial Design Engineering, TU Delft
Delft, the Netherlands
s.c.pont@tudelft.nl

TIM VAN DORTMONT
Industrial Design Engineering, TU Delft
Delft, the Netherlands
studio@drtmnt.com

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ABSTRACT

This paper aims to provide first insights into flash characteristics of bioluminescent microalgae as a potential media for future living light interfaces. A growing number of HCI and interaction design researchers show interest in living material interfaces, which incorporate living organisms for novel responsive behaviour and interaction possibilities in digital and biological hybrids. While much is known about the science of these organisms, their 'living aesthetics', i.e., how humans experience the unique temporal changes in a living media, have hardly been explored. To bridge this gap in designing living light interfaces, this paper presents a study of bioluminescent flash characterisation. A DIY shaking device was designed to interact with the liquid living media, providing a range of stimuli including orbital rotation, pulsation and vibration. The living light aesthetics is presented with rich visuals illustrating the intensity variations over time, textural qualities and spatial distribution.

AUTHORS KEYWORDS

Living aesthetics; living media interfaces; temporality; biodesign; bioluminescent microalgae.

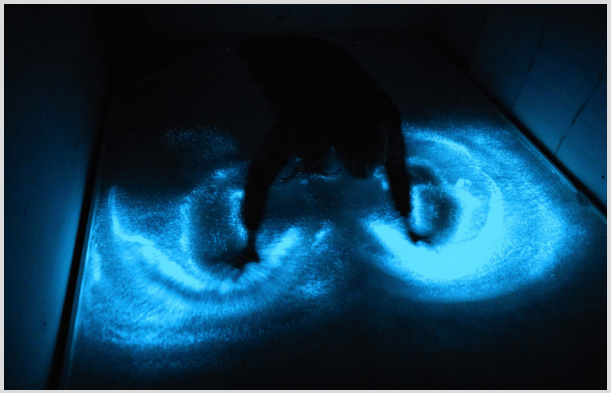
CSS CONCEPTS

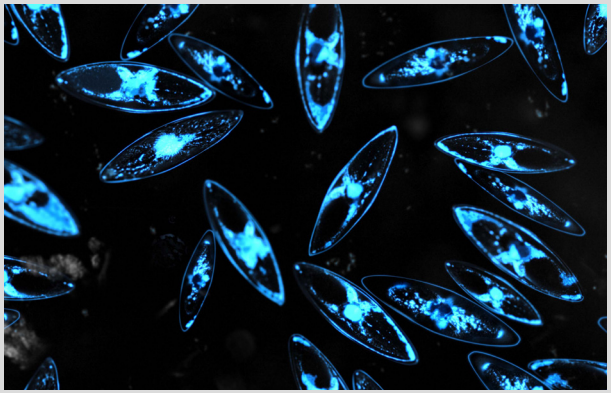
• Human-centered computing~ Interaction Design~ Interaction Design Theory, Concepts, and Paradigm

INTRODUCTION —

OVERVIEW OF BIOLUMINESCENCE
AND RELATED WORK

IMAGES 1-2
GLOWING NATURE BY DAAN ROOSEGAARDE
SOURCE: STUDIOROOSEGAARDE.NET





The capacity of living organisms to generate visible light has inspired design research and practice for alternative ways of illuminating and interface design. For example, bioluminescent organisms have been incorporated in a number of interactive installations, such as Glowing Nature by Studio Roosegaarde, Bioluminescent Field by Nicola Burggraf, Ambio by Tressa van Dongen and Biolum Due Bench [16], which allow the visitors to experience and interact with this natural phenomenon. In the artwork of Andreas Greiner [11], bioluminescent organisms are placed on the strings of a grand piano, working as an expressive display of the improvised piano piece.

While bioluminescence exists in a broad range of living organisms in nature (e.g., fungi and bacteria), bioluminescent dinoflagellates, a family of microalgae or phytoplankton (plant-like plankton) [45], are the only photosynthetic organisms that are capable of light emission by directly using solar energy [44]. Next to this unique quality, bioluminescent dinoflagellates are able to emit light in response to mechanical stimuli [41], which inspired us to further explore their potential in interactive artefacts.

The potential of bioluminescence as a regenerative illumination source and interaction media calls for new research initiatives aiming at a better understanding of what these organisms can offer to the fields of HCI and interaction design. Yet, there has been no systematic study to date exploring how these organisms behave in an interactive setup, and how humans experience the unique temporal changes in a living light media.

With the concept of Living Light Interfaces (LLI), we aim to discern this new design research space and emphasize the new aesthetics and interaction qualities of interfaces that incorporate bioluminescent microorganisms. Temporality of the living light is an important feature when working with bioluminescence. Hence, the concept of LLI synthesizes the two existing concepts of Ephemeral User interfaces [8] and Living Media interface [29] in studying these living and short-lived expressions. The concept of Ephemeral UIs explores the materiality aspects of user interfaces with elements that last for a limited time, such as soap bubbles [8], while Living Media Interfaces suggest incorporating living organisms in user interfaces [29].

One of the important aspects affecting the living light's temporal expression and its ephemerality is the physical state of the substrate (e.g., liquid, gel) where the microorganisms can thrive. Therefore, in the exploration of LLI, we focused on a single specific substrate at a liquid state. To that end, our work aims at bridging the experiential knowledge gap in designing LLIs by characterising the flash behaviour of bioluminescent microalgae in a liquid media.

Our explorations focus on a specific strain of dinoflagellates called pyrocystis fusiformis. The focus of our study is on how aspects of livingness come to expression in the living interface, i.e., their living aesthetics [17], concerning the relation between kinetic stimuli (input) and the quality of lighting (output). Through a range of controlled stimuli including orbital rotation, pulsation and vibration, we step towards an understanding of the algal bioluminescence and identify the varieties in interaction that can alter the flash qualities.

Before elaborating on the study results, we provide an overview of the related work under bioHCI and biodesign, the notion of temporality in HCI and the science and art of algal bioluminescence.

BIOHCI & BIODESIGN

Living materials are an emergent material class, infused with the productive, adaptive, and regenerative properties of living organisms [39]. In HCI, earlier studies at the crossovers of biology and design, framed under DIYbio, promoted tinkering and open access to biological tools, protocols and knowledge outside of professional settings [22, 54, 7, 10].

More recently, researchers proposed conceptual frameworks intended to inform HCI researchers who are new to the possibilities and challenges of working with microorganisms. For example, Pataranutaporn et al. [32] provide an analysis of research projects that integrate microorganisms as part of the computing system, and propose the notion of Living Bits to challenge the traditional boundaries between biological cells and computers [32]. Similarly, Merritt et al. [29] proposed Living Material Interfaces (LMIs) "as interfaces that incorporate living organisms and biological materials to take advantage of their qualities to enable different forms of interaction between humans and digital systems" (p. 3).

Karana et al. [17], in a recent article, extended the possibilities of living materials to everyday life, showcasing new aesthetics and advanced functionalities that are bound to 'livingness' as a material quality.

These strong concepts and frameworks suggest that working with living organisms requires a close collaboration between designers and biologists in bringing them to the everyday artefacts. Yet, there is a knowledge gap in design and HCI research when it comes to the unique temporal changes in living interfaces, i.e., their living aesthetics.

RELATED WORK —

BIOHCI, BIODESIGN AND THE SCIENCE / ART OF ALGAL BIOLUMINESCENCE

LIVING AESTHETICS

Temporal aspects of smart and living materials alike have been emphasized in HCI by many scholars over the last decade as an important factor in how interactive artefacts may be experienced [50, 4, 18]. From shape-memory alloys [6], electroluminescent materials [3], to fire, soap bubbles, the potentials of materials with unique temporal qualities have been revisited in designing user interfaces for their short-lived or ephemeral characteristics [8].

Karana et al. [17] elaborated on the temporal dimension of designing with living materials concerning how humans experience "the type, degree, and duration of change in a living artefact over time" (p. 45), primarily due to growth and reproduction, which they refer to as living aesthetics.

Aesthetics of a living interface, as like Ephemeral User Interfaces [8], might entail elements that last for a limited time. This is particularly relevant for the case of bioluminescent dinoflagellate, as the dynamic light produced by the living microorganism can only last for a second, which change over time (e.g., it can get brighter, or it can last longer) based on the wellbeing of the organism and the way we interact with it. But how do we characterize dynamic light?

CHARACTERISING DYNAMIC LIGHT

Dynamic lighting has been studied in relation to various fields of studies, including, augmented reality [1], design and architecture [36, 19, 21] and more fundamentally in optics and visual perception [e.g. 53, 30, 48]. The stimuli used in these studies range from indirect atmospheric light projection [e.g. 26] to direct LED light sources [e.g. 34]. In the later dynamic light output can be created by modulating brightness and spectral colour characteristics of LED light sources.

Louwers et al. [26] used dynamic light projections in their study of light experience and atmosphere perception. They characterized dynamic light texture in terms of (1) organisation of shapes/textures (deterministic or chaotic way), (2) form (geometric vs organic forms), (3) contrast of sharpness and brightness, and (4) dynamics (slow vs fast pace of all the changes above). Features 1-3 are in line with commonly conducted texture characterisation studies. For dynamic textures, feature 4 is a logical addition.

Petersen and Kristensen [34] designed an artificial dynamic lighting installation with LEDs to observe and explore adaptive couplings between dynamic artificial lighting and daylight. The dynamic artificial lighting in their interactive installation used algorithm-based intensity and light temperature variations across the space (animated and continuous 2D maps) to collectively control the behaviour of LEDs. The control parameters of the dynamic light output included (1) boundary ranges of luminous intensity and colour temperature, (2) speed of fluctuations (temporal composition) and (3) spread of the generated 2D map (spatial composition of fluctuations).

Dynamic lighting thus can have a wide range of applications from adaptive illumination (where the light source provides functional light) [e.g. 56] to communication [e.g. 40], to ambient user experience [e.g. 33] and dynamic appearance [e.g. 38]. The light produced by most bioluminescent dinoflagellates is only visible in a fairly dark environment, making them less suitable for primary lighting applications. However, it could be used for 'wayfinding' in the dark [16] and enhancing the livelihood and experience of spaces through dynamic texture and 'brilliance' [cf. 36, 19].

Textural quality of light, intensity variations over time and across space form are a scientifically-informed start for dynamic lighting characterization studies, irrespective of the type of light source. This serves as a point of departure in navigating how bioluminescence might be characterized, which is a contribution of the presented work. Accordingly, we characterized the flash characteristics of bioluminescent microalgae in terms of intensity variations, spatial distribution, and textural qualities of the light output.

SCIENCE AND ART OF BIOLUMINESCENCE

The evolutionary purpose of bioluminescence is assumed to be for defence, offence or communication [12, see 28 for a review]. Not surprisingly, most of the early scientific work on bioluminescent microorganisms have been produced in the fields of marine biology and ecology [e.g. 13, see 49 for a review]. More recently, bioluminescence has been studied in biotechnology and biochemical engineering to study bacterial pathogens, detect food toxicity, and track cells of interest in vivo [55, 39]. Scientists in the field of chemical engineering at MIT have explored possibilities of bringing bioluminescence as an alternative regenerative energy source by incorporating nanoparticles containing enzymes from bioluminescent organisms in plants [23].

Dinoflagellates are responsible for most of the blue bioluminescence observed in the surface ocean [47]. Through photosynthesis, dinoflagellates produce a large amount of oxygen, influencing the concentrations of oxygen and carbon dioxide in Earth's atmosphere [46]. Cultures of bioluminescent dinoflagellates are regulated by a biological (circadian) clock. This clock regulates the internal process for a photosynthetic period during which the organisms cannot emit any appreciable light and a corresponding luminescent or emitting period [20, 44]. The most well-known species of bioluminescent dinoflagellates are those of the pyrocystis genus, which are often referred to as the fireflies of the sea [35].

In general, bioluminescent dinoflagellates are known to have two distinct ways of emitting light: flashing and glowing. The most commonly seen and described form of bioluminescence among dinoflagellates is flashing, which is the production of short discontinuous bursts of light. Flashing primarily occurs when shear stress is induced on the microscopic cell [27], through hydrodynamic movements, for example when larger animals swim by or waves break on the surface [37].

A cascade of cellular processes is involved in between exertion of shear stress on the outside of the cell membrane and the production of light in the responsible organelles containing the luciferin substrate, the luciferase enzyme, which are the main components responsible for the production of light [31, 49]. The emitted bioluminescence is mainly expressed in the blue-green part of the visible light spectrum between 450 to 490nm [14].

Previous research shed light on the biological or mechanical characterisation of the light produced by dinoflagellates [e.g. 5]. Commonly described characteristics include: the absolute photon emissions of a single cell [42] and the amount of force required to trigger bioluminescence [25]. Latz et al. [24] explain that in a small volume of liquid medium, bioluminescence is stimulated in presence of physical barriers as well as an abrupt hydrodynamic drag. Accordingly, an application of dinoflagellate bioluminescence as a flow visualization tool for regions of high shear has been proposed [25, 37].

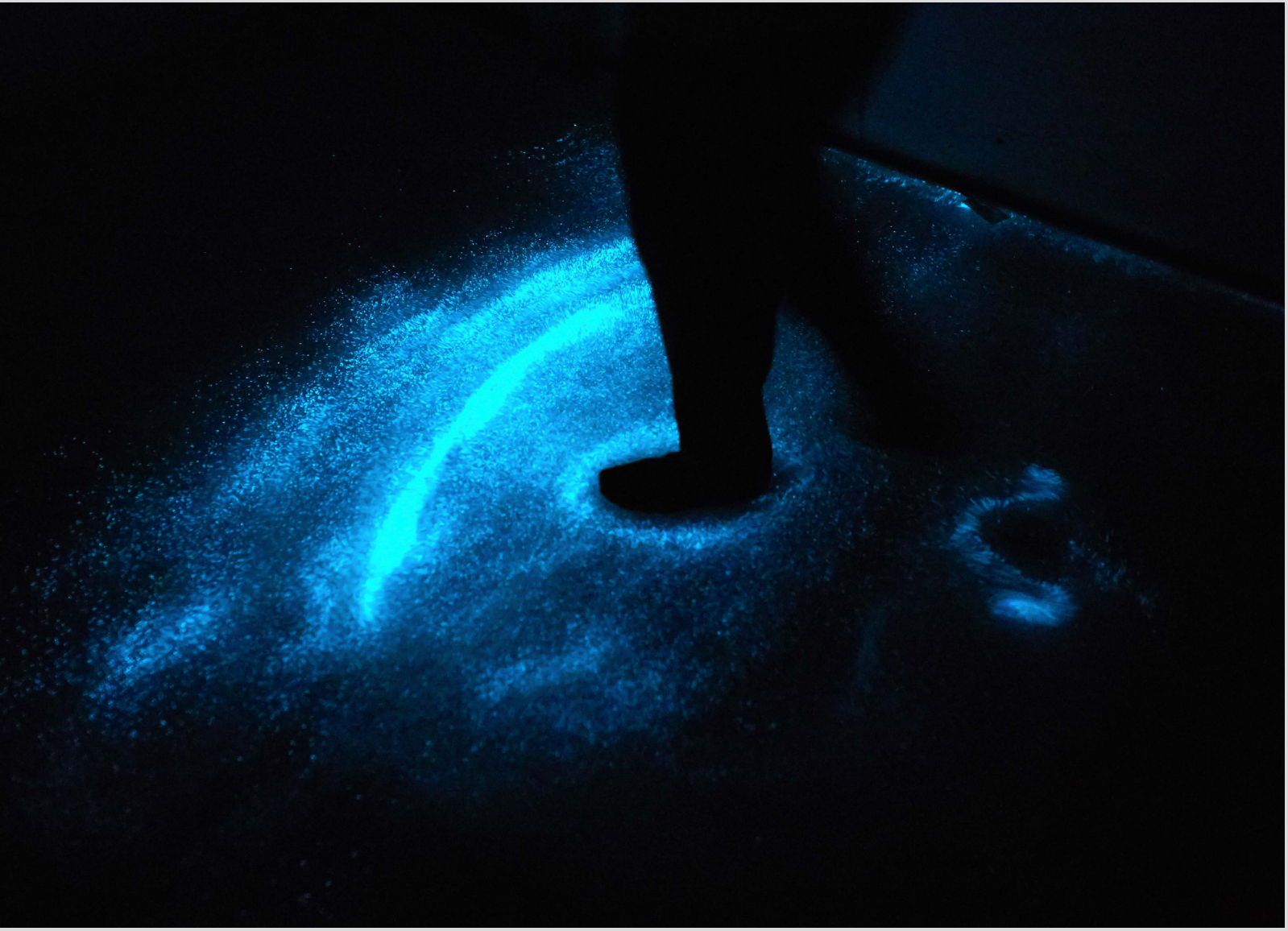


IMAGE 3
GLOWING NATURE BY DAAN ROOSEGAARDE
SOURCE: STUDIOROOSEGAARDE.NET

Dinoflagellate bioluminescence has been used in art installations, such as Growing Light by Studio Roosegaarde and the Bioluminescent Field by Nicola Burggraf. A common theme of these interactive setups is to allow visitors to explore the behaviour of the bioluminescent dinoflagellates through movement; in a way by replicating the interactions that would happen within the natural habitat of the organisms.

Glowing Nature uses transparent polymer bags embedded into the floor, which are filled with a large amount of media containing dinoflagellates. As visitors walk over the tiles, the algae within the tiles will be triggered by the force that is generated, in a way mimicking the experience of walking through a bunch of bioluminescent dinoflagellates as they are washing up onto the shore. The Bioluminescent Field consists of a dark room filled with a large number of small flasks containing the bioluminescent dinoflagellates. As the containers are attached to moving rods, the vials will start to move once visitors walk through the installation, which in turn triggers the bioluminescence of the algae.

GROWING LIGHT —

CREATING A SUSTAINABLE LIVING ENVIRONMENT
FOR THE ORGANISMS

Incorporating living organisms in designing interfaces asks for first growing them and perpetuating the living culture. In order to do so, the knowledge of habitats where the microorganism is found is critical. There is an existing body of knowledge on how various microorganisms can be grown in the lab environment. These studies specify, for instance, the environmental conditions, the chemical and biotic composition of the growth media, frequency of filtering the biomasses due to overpopulation, adding or renewing media. This information is most likely provided by the supplier of a specific strain used in the design process. For our experiments, we worked with 300ml pyrocystis fusiformis algae cultures from PyroFarms, which we split in three sterile Erlenmeyer flasks, capped with non-absorbent cotton wool (allowing for sufficient airflow and gas exchange).

In order to effectively grow and maintain the dinoflagellate cultures, a dedicated setup was created. We modified Severin KS 9889 wine cooler at Biolab (Science Center, TU Delft) to keep our algae cultures. This cooler allowed for a constant temperature, ranging from 14 to 16 degrees Celsius. As it is crucial to keep a circadian lighting regime when growing photosynthetic dinoflagellates, a lighting panel, consisting of 120 cool-white (3528 SMD, 5500K) LEDs has been attached to the front door of the cooler. The panel provides the algae with approximately 800 lumens during a 14-hour light cycle, while blocking exposure to the surrounding light, once the LEDs are off during a 10-hour dark cycle. The 14:10 light-dark regime made possible by an analog power outlet timer (12V). All the experiments were conducted one hour after the start of the dark cycle.

IMAGE 4
GROWING SETUP WITHIN COOLER

IMAGE 5
TRANSFER OF CULTURES

IMAGE 6
SETUP TO CAPTURE LIVING LIGHT

CAMERA SETTING TO CAPTURE THE LIVING LIGHT

NIKON D5500 + NIKKON 50MM F/1.4 G LENS

RESOLUTION: 1920X1080 AT 50FPS

APERTURE: F/2
SHUTTER SPEED: 1/50
ISO: 800

IMAGE 7
THE DIY SHAKING DEVICE

A DIY SHAKER —

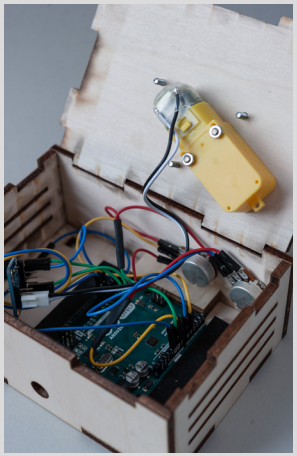
DESIGNING AN ORBITAL SHAKING DEVICE

In order to be able to consistently perform different types of kinetic stimuli, an orbital shaker was built. The orbital shaker consists of three main components: the base housing the electronics, the rotating arms translating the rotation of the motor, and the top plate holding the containers. At the core of the shaker is the 6-volt DC motor, which can be controlled with the use of an Arduino Uno. In addition, two potentiometers, one for controlling the speed of the motor and one for switching between the agitation patterns, have been added. Different types of holders have been made in order to securely hold various sizes of Erlenmeyer flasks. The rotating arms make use of ball bearings to reduce friction, resulting in a smooth and consistent rotation.

Two types of attachments were made in order to stimulate the algae in various ways: an orbital shaking top and a vibration plate. The vibration plate consists of 7 small vibration coin motors mounted on a wooden plate, which are able to vibrate at speeds of around 3000 to 10.000 rpm depending on the voltage supplied. Both fit on the same base and are controlled with the same Arduino Uno, allowing for easy use.

The relatively simple design of the DIY shaker enabled a large variety of kinetic stimuli by adjusting only a few parameters, including the power of the motor, the direction of rotation and the duty cycle.

IMAGE 8-9
DETAILS OF THE SHAKER



KINETIC STIMULI —

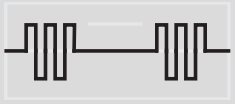
AN OVERVIEW OF THE VARIOUS STIMULI PATTERNS

We explored the relations between three main types of kinetic stimuli, namely rotation, vibration and pulse, and the living light output. The table below shows the 18 various patterns within these three stimuli that were tested in the study.

Rotational stimuli are generated by a full cycle or 360-degree rotation of the base, inducing a swirling movement within the liquid. We tested nine variations within rotation, by changing the rotation direction, duty cycle (relative duration of ON/OFF states referred to as pause intervals) and motor speed (90 rpm and 120 rpm).

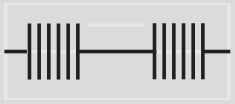
R1	R2	R3	R4-5	R6
90 RPM - CONTINUOUS	120 RPM - CONTINUOUS	120 RPM - SINGLE ROTATION	120 RPM - ALTERNATING - 1&2 SEC PAUSE	120 RPM - RAMPED ALTERNATING

Pulse stimuli is generated by restraining the degree of rotation to 20 ms (5 degrees) before alternating the rotation direction at 120 rpm rotation speed. The four variations were generated by changing the number of the back and forth pulsation (3, 5), duration (single 3-pulse with intervals or continuous).

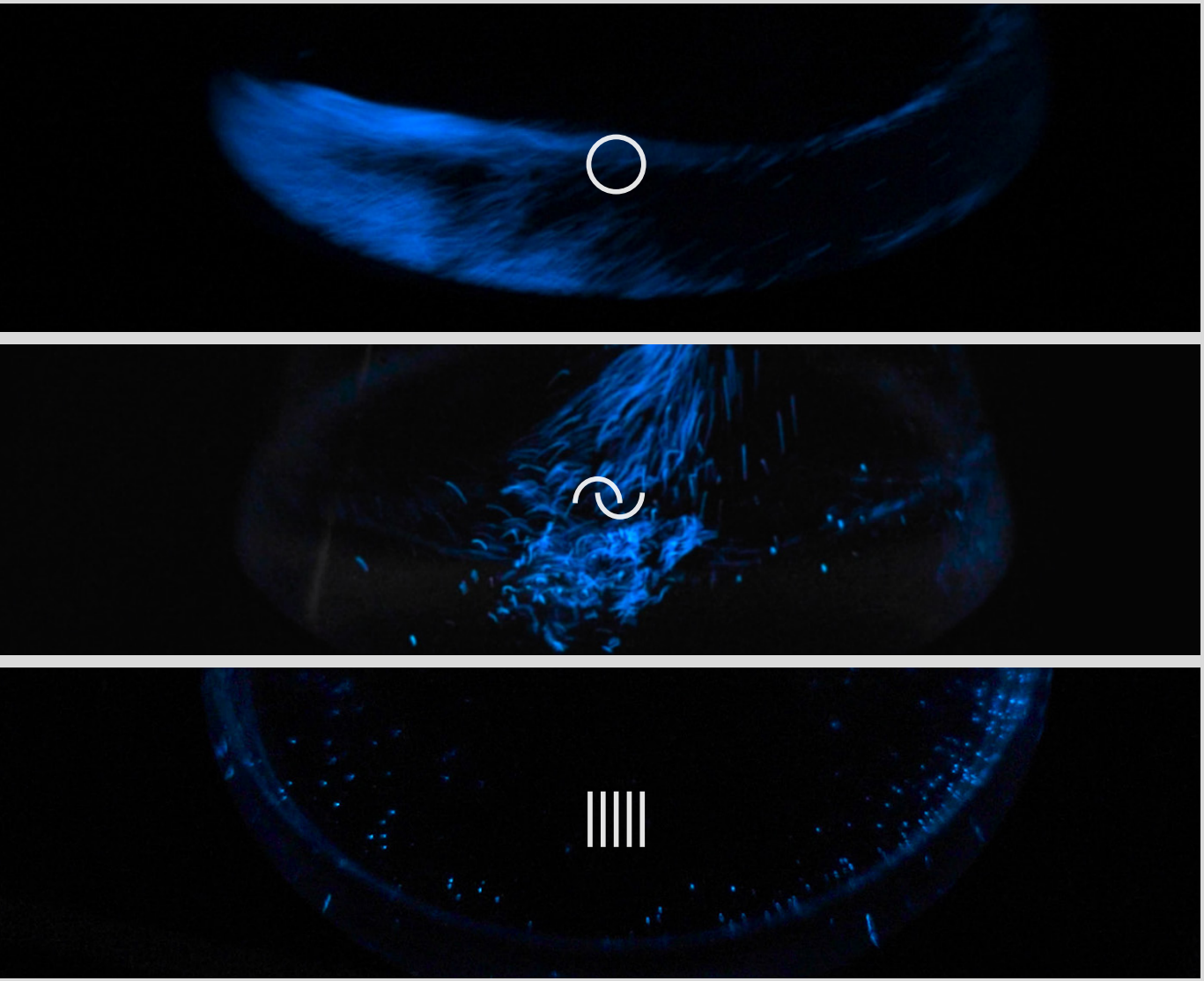


P1	P2	P3	RP1-2
120 RPM - 20MS - 3 PULSES - 2 SEC PAUSE	120 RPM - 50MS - 3 PULSES - 2 SEC PAUSE	120 RPM - 100MS - 5 PULSES - 2 SEC PAUSE	120 RPM - ROTATION - PULSE - 10 MIN PAUSE

Vibration variations were generated mainly by changing the duty cycles on full power (5V) resulting in continuous vibration or vibrations with an interval (100 and 200 ms with 1 sec pause intervals).



V1	V2	V3
CONTINUES VIBRATION	WITH INTERVALS - 100MS - 1 SEC PAUSE	WITH INTERVALS - 200MS - 1 SEC PAUSE



IMAGES 10-12
ROTATION, PULSE & VIBRATION RESPONSES

RESULTS —

FLASH CHARACTERIZATION OF BIOLUMINESCENT ALGAE

In this section, we report on the qualities of the emitted light in terms of intensity variations over time, spatial distribution and textural qualities in relation to the three kinetic stimuli. In general, three movements could be induced in the liquid culture corresponding to the kinetic stimuli: swirling movement, side to side movement and localized disturbances. The presented visuals are a selection of the studied light outputs that capture significant variations among the 18 stimuli (see [51] for a complete overview).

INTENSITY VARIATION OVER TIME —

A MATLAB script was used as a base for analysing intensity variation in the video footage [2]. Reading the living light video files frame by frame, the script makes it possible to extract various types of information, such as the mean or max grey values. The mean luminance value of all pixels within the frame is calculated and plotted for each individual frame.

Different types of kinetic stimuli appear to have different effects on the delay, rise and decay of the light. For example, in constant rotation (R1) there is a steep linear rise until it reaches its peak at T85. At this point the light intensity drops with a similarly linear steepness, until it rises again at T105.

For 3-pulse with 1-sec intervals (P1), the intensity peak is reached at approximately T70. From this point on, the light intensity drops with a similarly linear steepness, until it rises again at T90 or T100.

A cross comparison between the intensity variation graphs indicates that on average mean luminance values are the highest when alternating the rotation (R4-5) and lowest for vibration (V1-3). This significant boost in light intensity appears to be caused by an increase in shear force resulting from the sudden change of direction.

Our results also show that when rotational speed is increased (R2), the peak and total amount of light produced over time will increase as well. However, a faster rotational speed will also result in a more rapid and visually noticeable drop in intensity over time.

IMAGE 13
RESPONSE OF R1 AND R2

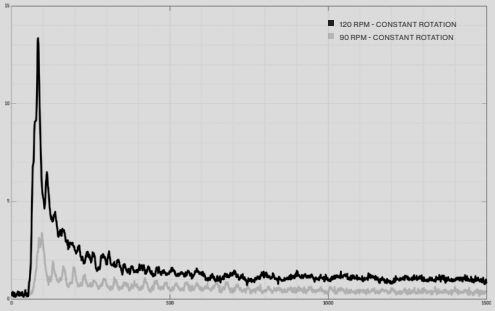
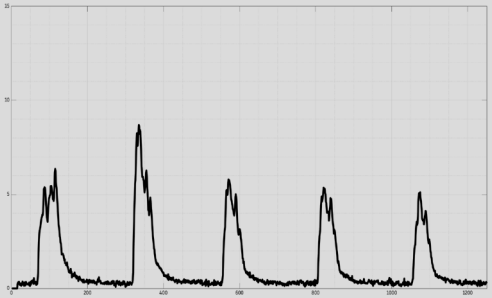
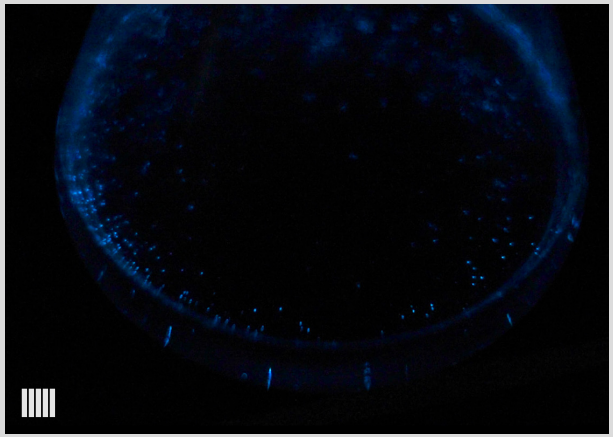
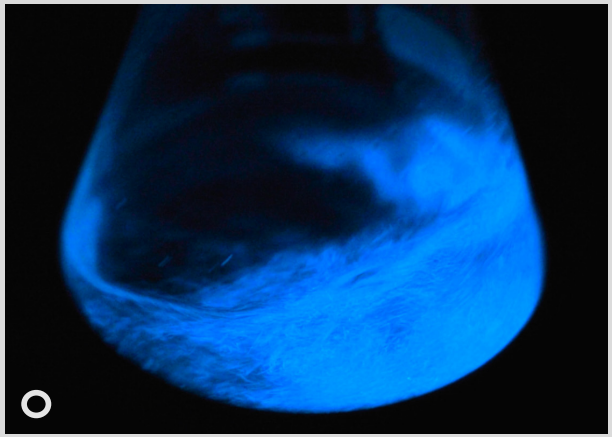


IMAGE 14
RESPONSE OF P1



IMAGES 15-16
VARIATION IN INTENSITY BETWEEN ROTATION (R4-5) AND VIBRATION (V1-3)





In pulsation compared to alternating rotation, the high intensity flashing behaviour faded more quickly. The results also show that when pulsation is sequenced after rotation with a 10 min interval (PR1 vs PR2), the culture shows a significantly lower light intensity.

Lower intensity in vibration (V1) can be explained due to a relatively smaller number of flashing cells being stimulated at the time. The culture is able to recover from vibration and retain the same level of luminance value when exposed to a large shear force, for example a high-speed rotation.

LOSS OF SENSITIVITY

The dinoflagellates become less sensitive to specific stimuli over time. Once a culture is exposed to a large shear force, such as a high-speed rotational movement (R2), it appears to lose some of its sensitivity and show almost no bioluminescent response to following, more gentle stimuli. Loss of sensitivity seems to be responsible for a noticeable decrease in perceived brightness and overall shorter periods of visible light in constant rotational movement [52].

DURATION OF LIGHT EMISSION (AND FADING)

When moved continuously at full speed (R2), the culture emits visible light for about 30 seconds. However, our results show that the duration of light emission is highly dependent on the type of stimuli. In alternating rotation (R4-5), for instance, the light emission lasts for over 300 seconds.

DELAY IN RESPONSE

The response curves of the light were also analysed with regards to different types of mechanical stimulation, where we looked at the relation between input and output, e.g., measuring the initial delay and the fading duration after the movement stops. We noticed the initial delay in response was affected by both the type of mechanical stimuli, and the freshness of the liquid culture [24]. A 'fresh' culture, which has not been stimulated before, compared to a previously stimulated one, resulted in shorter delay in response.

IMAGE 17
INPUT-OUTPUT RELATION

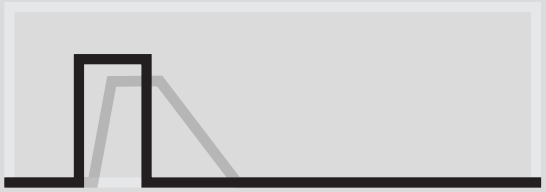


IMAGE 18
DURATION OF LIGHT EMISSION (R2 AND R4-5)

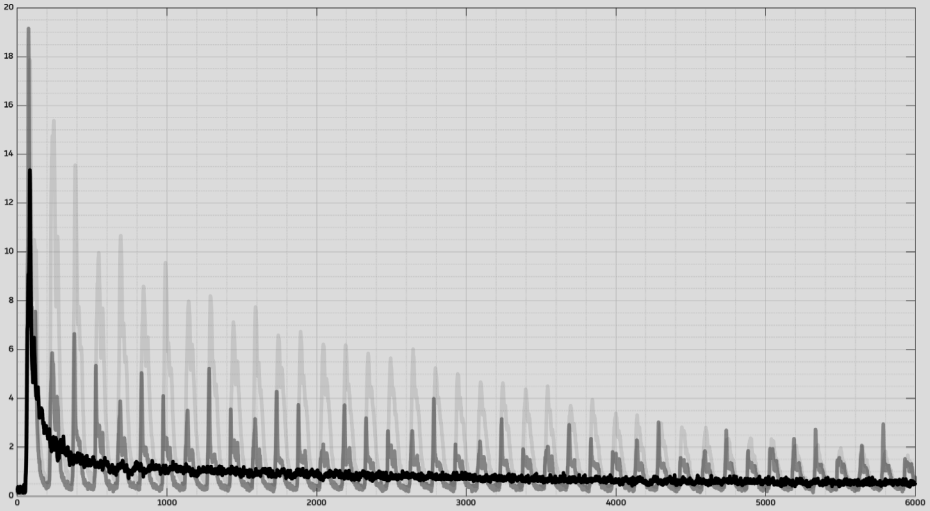
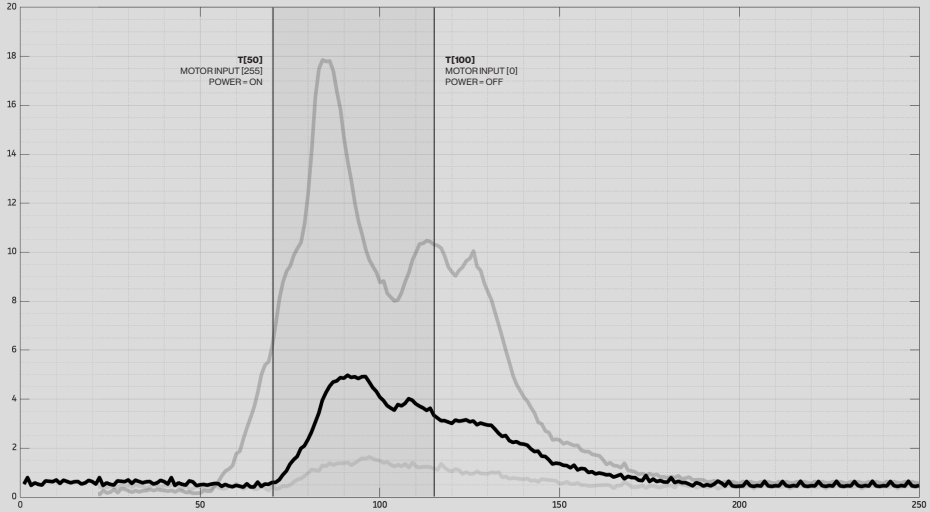


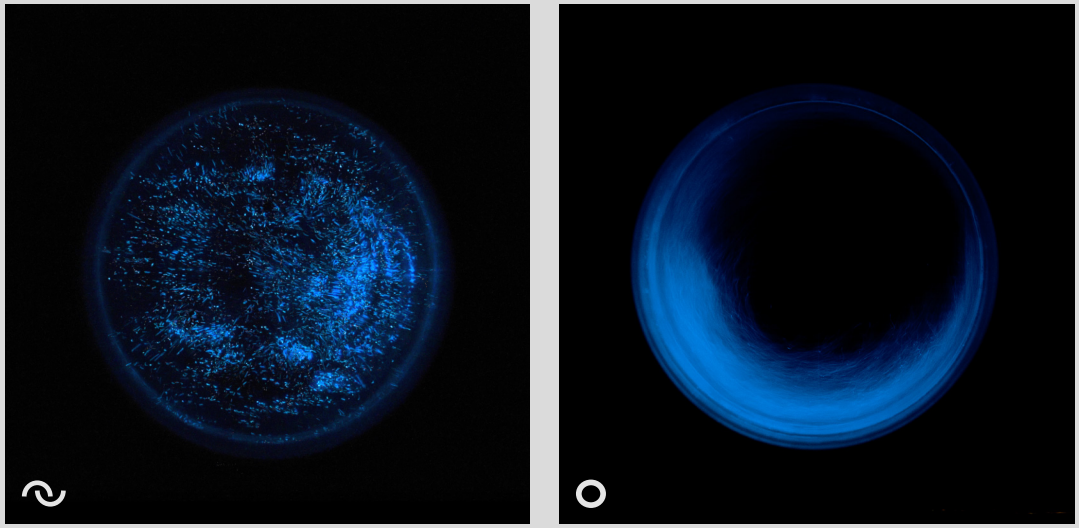
IMAGE 19
DELAY IN RESPONSE



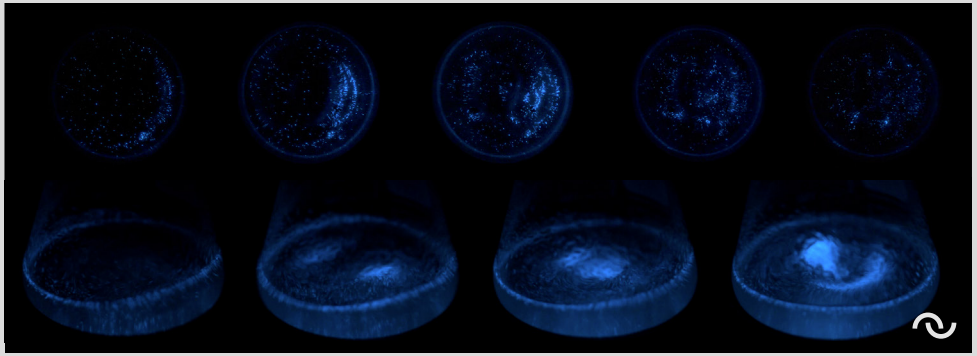
SPATIAL DISTRIBUTION —

The movement of the light inside the container [pattern of light] differs depending on the type of kinetic stimuli. We used long exposure trajectories of the moving light pattern and frame-by-frame propagation of the pattern.

Previous research suggests that existing fluid dynamics models, such as laminar and turbulent flow can be relevant in describing the dynamics of the observed pattern [25]. Our results attest to such a mechanical relationship between the fluid dynamics and the emergence and propagation of the living light pattern. Thus, any parameter that governs the fluid dynamics, including the shape of a container, volume and density of the culture (affected by media and cell density) can have influence on the spatial and temporal shape of living light. We observed that the bioluminescent cells may stick to the container walls as well as to one another. The former was evident particularly when we applied rotational stimuli, where the floating cells were centrifuged to the side walls.



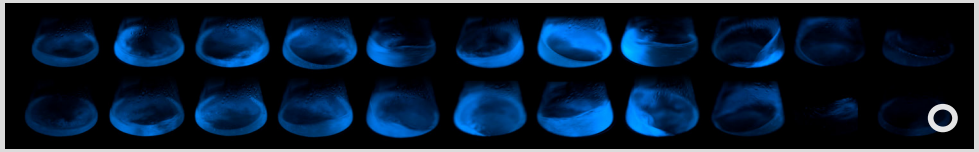
IMAGES 20
LONGE EXPOSURE PHOTOGRAPHS SHOWING THE LIGHT DISTRIBUTION IN P1 (LEFT) AND R1 (RIGHT).



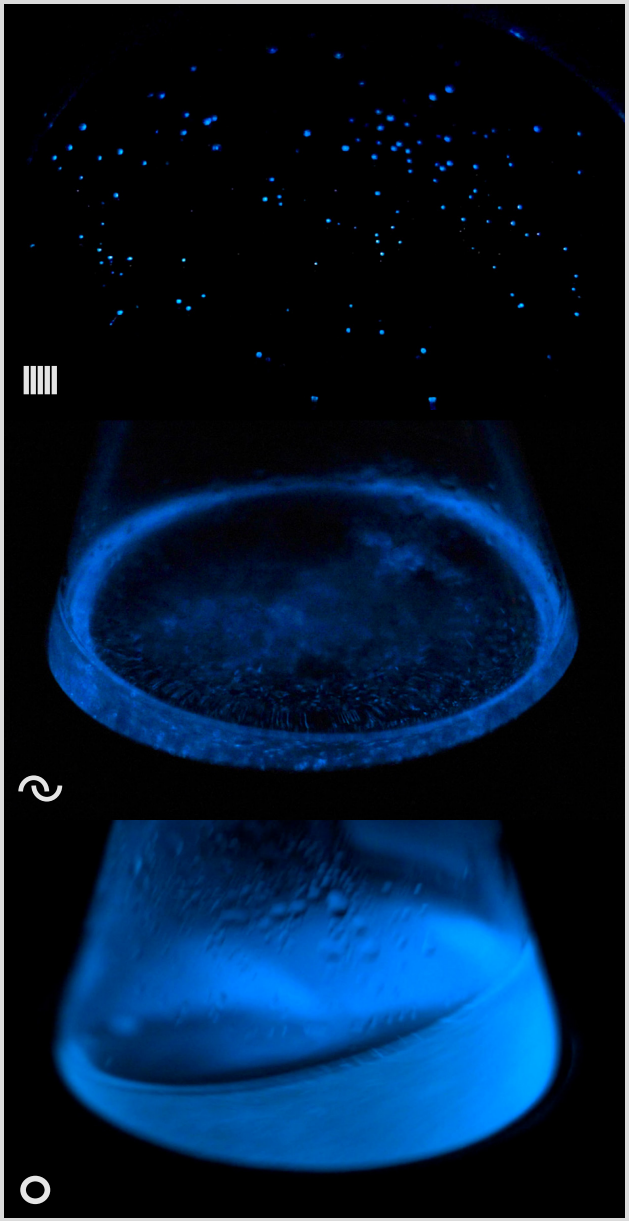
Induced by the back and forth tides in the liquid (P1), an interesting pattern was observed. First, the cell concentration near the edge of the glass lights up. At the point when the light on the edge starts to fade, a cluster of algae at the centre illuminates, creating a bright cluster of light. This is most likely caused by the ripples within the liquid colliding in the middle of the container.

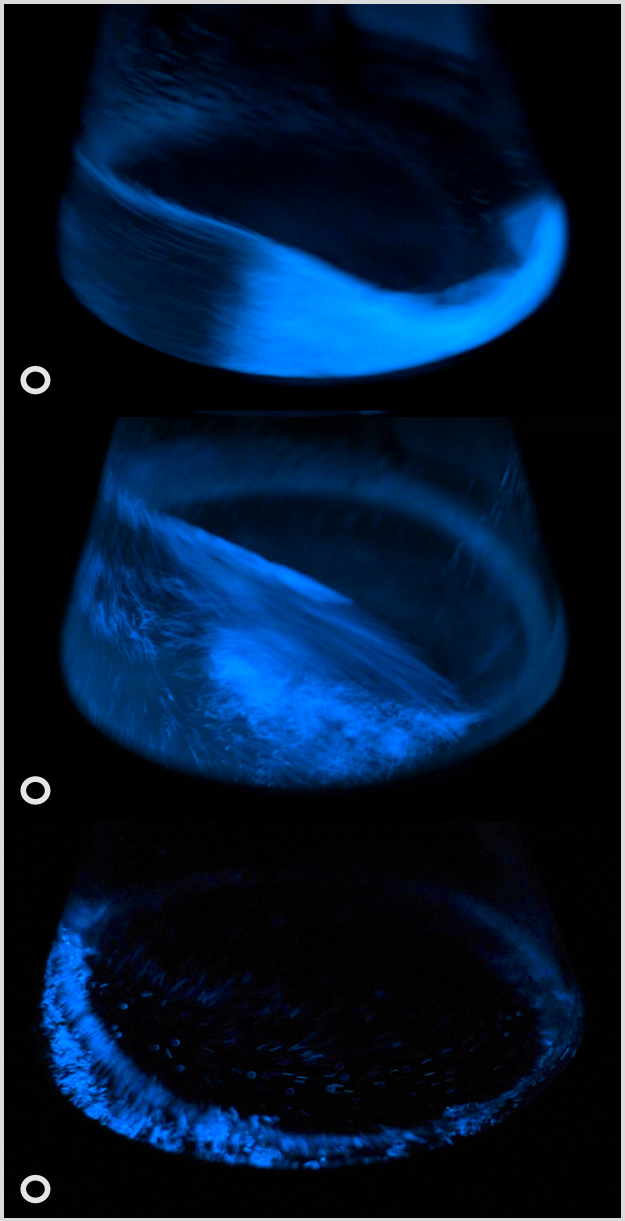
Our results show that the liquid volume can also play as a parameter in the spatial distribution of light and its overall living aesthetics.

IMAGES 21
FRAME-BY-FRAME PROPAGATION OF LIGHT PATTERN IN P1.



IMAGES 22
FRAME-BY-FRAME PROPAGATION OF LIGHT PATTERN IN R1 (ALTERNATING ROTATION). ROTATIONAL DIRECTION CHANGES FROM COUNTERCOCKWISE (TOP ROW) TO COCKWISE (BOTTOM ROW) .





TEXTURAL QUALITIES —

In addition to the footage used for the spatial distribution analysis, we generated close-up images of local areas to get a better view on the textural qualities.

As the rotational force pushes most bioluminescent cells into a tight cluster near the edge of the glass, the individual dots of light start to blend together. Therefore, rotational stimuli result in more of a uniform glow with barely any visible texture. Moreover, a higher rotational speed will lead to an even finer uniform line.

Pulsation and vibration tend to create highly textured lighting patterns as cells throughout the whole liquid are triggered, but not pushed together as much, often resulting in a highly scattered light.

The density of a culture and the number of cells within the liquid medium also influences the perceived texture. As the density increases, individual dots will sit closer to each other and appear to blend together. The refractive properties of the cells themselves are assumed to have an effect on the textural qualities. Within a denser culture, the light emitted by the organism has to pass through more cell matter, which results in a more diffused light.

IMAGE 23
VARIATIONS IN TEXTURAL QUALITIES AMONG DIFFERENT KINETIC STIMULI (LEFT) AND ROTATIONAL STIMULI (RIGHT)

IMAGE 24
PROTOTYPE OF DEVICE

FUTURE WORK —

FOR FURTHER RESEARCH

IMAGE 25
CLOSE-UP OF PROTOTYPE

In this paper, we present a study exploring the living aesthetics of bioluminescent algae in a liquid media, by interacting with it in three ways: rotating, vibrating, and pulsating. Through 18 various patterns under these three kinetic stimuli, we characterized the intensity of light, its textural qualities, and spatial distribution in a living liquid media.

Our study is a unique contribution to the BioDesign and BioHCI communities by providing for the first time an insight into the responsive behaviour of these living organisms, as potential media for interactive artefacts. With the concept of Living Light Interfaces (LLI), we hope to inspire future research in HCI and design communities in exploring this new design research space, towards novel aesthetics and interaction qualities of interfaces that incorporate bioluminescent microorganisms.

In the next studies, we aim to explore how the unique living aesthetic of such LLIs would change the way people interact with them in the real-life settings, i.e., performativity [9], and how this ultimately evokes unique care practices in the use time of these LLIs, i.e., mutualistic care [17].

We recommend future characterisation studies on the texture and spatial distribution, particularly to help with the development of tools for designers to explore and visualize the living light effects. Such specialized tools for a better understanding of textural qualities and spatial distribution of a living light will enable light designers in the exploration of this yet unexplored territory in design.

In the attempt to illustrate our characterisation results, we designed a LLI for the exhibition STILL ALIVE [16]. The first iteration of the design was focused on improving the artefact stability and the shaker power. We incorporated a metal frame and a stronger DC motor to have a more distinguished difference between the slow and fast rotational speed and the possibility to gradually ramp the speed, which was not possible with the initial shaker. For the next iterations, we plan to map the kinetic stimuli to input from visitors, by incorporating for instance a manual input device and sensors to detect the visitors' movement and proximity to the LLI. With that, we hope to further develop an understanding of the links between living light qualities and the fundamental concepts of interaction such as input/output [15].

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REFERENCES

[1] A. Alhakamy and M. Tuceryan. 2019. AR360: Dynamic Illumination for Augmented Reality with Real-Time Interaction. In *2019 IEEE 2nd International Conference on Information and Computer Technologies (ICICT)*. 170–174.

[2] Image Analyst. 2008. *Video Processing Tutorial*. Retrieved Feb 10, 2021 from https://www.mathworks.com/matlabcentral/fileexchange/47726-video-processing-tutorial

[3] Bahareh Barati, Elisa Giaccardi, and Elvin Karana. 2018. *The Making of Performativity in Designing [with] Smart Material Composites*. Association for Computing Machinery, New York, NY, USA, 1–11.

[4] Jenny Bergström, Brendon Clark, Alberto Frigo, Ramia Mazé, Johan Redström, and Anna Vallgårda. 2010. Becoming materials: material forms and forms of practice. *Digital Creativity* 21, 3 (2010), 155–172.

[5] WH Biggley, E Swift, RJ Buchanan, and HH Seliger. 1969. Stimulable and spontaneous bioluminescence in the marine dinoflagellates, Pyrodinium bahamense, Gonyaulax polyedra, and Pyrocystis lunula. *The Journal of general physiology* 54, 1 (1969), 96–122.

[6] Marcelo Coelho, Ivan Poupyrev, Sajid Sadi, Roel Vertegaal, Joanna Berzowska, Leah Buechley, Pattie Maes, and Neri Oxman. 2009. Programming Reality: From Transitive Materials to Organic User Interfaces *(CHI EA '09)*. Association for Computing Machinery, New York, NY, USA, 4759–4762.

[7] Kristin N Dew and Daniela K Rosner. 2018. Lessons from the woodshop: Cultivating design with living materials. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. 1–12.

[8] Tanja Döring, Axel Sylvester, and Albrecht Schmidt. 2013. A Design Space for Ephemeral User Interfaces. In *Proceedings of the 7th International Conference on Tangible, Embedded and Embodied Interaction (TEI '13)*. New York, NY, USA, 75–82.

[9] Elisa Giaccardi and Elvin Karana. 2015. Foundations of Materials Experience: An Approach for HCI. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems (CHI'15)*. 2447–2456.

[10] 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*. 55–64.

[11] Andreas Greiner. 2015. *From Strings To Dinosaurs, sound inducing bioluminescent light*. Retrieved Feb 10, 2021 from http://www.andreasgreiner.com/works/from-strings- to-dinosaurs/

[12] Steven HD Haddock, Mark A Moline, and James F Case. 2010. Bioluminescence in the sea. *Annual review of marine science* 2 (2010), 443–493.

[13] JW Hastings. 1983. Chemistry and control of luminescence in marine organisms. *Bulletin of marine science* 33, 4 (1983), 818–828.

[14] P. J. Herring. 1983. The Spectral Characteristics of Luminous Marine Organisms. *Proceedings of the Royal Society of London. Series B, Biological Sciences* 220, 1219 (1983), 183–217.

[15] Hiroshi Ishii and Brygg Ullmer. 1997. Tangible Bits: Towards Seamless Interfaces between People, Bits and Atoms. In Proceedings of the ACM SIGCHI Conference on Human Factors in Computing Systems (CHI '97).

[16] Elvin Karana. 2020. Still alive: *Livingness as a material quality in design*. Centre of Applied Research for Art, Design and Technology, Avans University.

[17] Elvin Karana, Bahareh Barati, and Elisa Giaccardi. 2020. Living artefacts: Conceptualizing livingness as a material quality in everyday artefacts. *International Journal of Design* 14, 3 (2020), 37– 53.

[18] E. Karana, N. Nimkulrat, E. Giaccardi, K. Niedderer, and J. N. Fan. 2019. Alive. Active. Adaptive: Experiential knowledge and emerging materials. *International Journal of Design* 13, 2 (2019), 1–5.

[19] Richard Kelly. 1952. Lighting as an Integral Part of Architecture. *College Art Journal* 12, 1 (1952), 24–30.

[20] Rosemarie Knaust, Thomas Urbig, Liming Li, Walter Taylor, and J Woodland Hastings. 1998. The circadian rhythm of bioluminescence in Pyrocystis is not due to differences in the amount of luciferase: A comparative study of three bioluminescent marine dinoflagellates. *Journal of phycology* 34, 1 (1998), 167–172.

[21] Andre Kuijsters, Judith Redi, Boris de Ruyter, and Ingrid Heynderickx. 2015. Lighting to Make You Feel Better: Improving the Mood of Elderly People with Affective Ambiences. *PLOS ONE* 10, 7 (07 2015), 1–22.

[22] Stacey Kuznetsov, Carrie Doonan, Nathan Wilson, Swarna Mohan, Scott E Hudson, and Eric Paulos. 2015. DIYbio things: open source biology tools as platforms for hybrid knowledge production and scientific participation. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*. 4065–4068.

[23] Seon-Yeong Kwak, Juan Pablo Giraldo, Min Hao Wong, Volodymyr B Koman, Tedrick Thomas Salim Lew, Jon Ell, Mark C Weidman, Rosalie M Sinclair, Markita P Landry, William A Tisdale, et al. 2017. A nanobionic light-emitting plant. *Nano letters* 17, 12 (2017), 7951–7961.

[24] Michael I. Latz, Michelle Bovard, Virginia VanDelinder, Enrico Segre, Jim Rohr, and Alex Groisman. 2008. Bioluminescent response of individual dinoflagellate cells to hydrodynamic stress measured with millisecond resolution in a microfluidic device. *Journal of Experimental Biology* 211, 17 (2008), 2865–2875.

[25] Michael I Latz, Jennifer C Nauen, and Jim Rohr. 2004. Bioluminescence response of four species of dinoflagellates to fully developed pipe flow. *Journal of plankton research* 26, 12 (2004), 1529– 1546.

[26] Gijs Louwers, Sylvia Pont, Martin Havranek, and Mitchel van Zuijlen. 2008. *Designing with Dynamic Light Textures: Enlightening Designers*. Retrieved Feb 10, 2021 from https://www.led-professional- symposium.com/design-lectures

[27] Elisa M Maldonado and Michael I Latz. 2007. Shear-stress dependence of dinoflagellate bioluminescence. *The Biological Bulletin* 212, 3 (2007), 242–249.

[28] Charlotte LJ Marcinko, Stuart C Painter, Adrian P Martin, and John T Allen. 2013. A review of the measurement and modelling of dinoflagellate bioluminescence. *Progress in Oceanography* 109 (2013), 117–129.

[29] 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.

[30] Yaniv Morgenstern and Daniel J Kersten. 2017. The perceptual dimensions of natural dynamic flow. *Journal of vision* 17, 12 (2017), 7–7.

[31] MT Nicolas, BM Sweeney, and JW Hastings. 1987. The ultrastructural localization of luciferase in three bioluminescent dinoflagellates, two species of Pyrocystis, and Noctiluca, using anti-luciferase and immunogold labelling. *Journal of cell science* 87, 1 (1987), 189–196.

[32] Pat Pataran, David S Kong, Pattie Maes, and Misha Sra. 2020. Living Bits: Opportunities and Challenges for Integrating Living Microorganisms in Human-Computer Interaction. In *Proceedings of the Augmented Humans International Conference (AHs '20)*. 75–82.

[33] Milica Pavlovic, Sara Colombo, Yihyun Lim, and Federico Casalegno. 2018. Designing for ambient UX: case study of a dynamic lighting system for a work space. In *Proceedings of the 2018 ACM International Conference on Interactive Surfaces and Spaces (ISS '18)*. 351–356.

[34] Kjell Yngve Petersen and Ole Kristensen. 2017. The Experience of Dynamic Lighting. In *Proceedings of the Conference on Design and Semantics of Form and Movement-Sense and Sensitivity, DeSForM 2017*. IntechOpen.

[35] Vincent Pieribone and David F Gruber. 2005.*A glow in the dark: the revolutionary science of biofluorescence*. Harvard University Press.

[36] Sylvia C. Pont. 2019. Light: Toward a Transdisciplinary Science of Appearance and Atmosphere. *Annual Review of Vision Science* 5, 1 (2019), 503–527.

[37] J Rohr, M I Latz, S Fallon, J C Nauen, and E Hendricks. 1998. Experimental approaches towards interpreting dolphin-stimulated bioluminescence. *Journal of Experimental Biology* 201, 9 (1998), 1447–1460.

[38] Daniel Saakes, Hui-Shyong Yeo, Seung-Tak Noh, Gyeol Han, and Woontack Woo. 2016. Mirror mirror: An on-bodyt-shirt design system. In Proceedings of the 2016 CHI conference on human factors in computing systems. 6058–6063.

[39] Shrikrishnan Sankaran, Shifang Zhao, Christina Muth, Julieta Paez, and Aránzazu Del Campo. 2018. Toward light regulated living biomaterials. *Advanced Science* 5, 8 (2018), 1800383.

[40] Thomas Schielke. 2015. Influence of lighting design on marketing communication.*Leukos* 11, 3 (2015), 109–124.

[41] HH Seliger and WD McElroy. 1968. Studies at Oyster Bay, Jamaica, West Indies: I. Intensity patterns of bioluminescence in a natural environment. *Journal of Marine Research* 26, 2 (1968), 244–255.

[42] H. H. Seliger, W. H. Biggley, and E. Swift. 1969. Absolute values of photon emission from the marine dinoflagellates Pyrodinium Bahamense, Gonyaulax Polyedra and Pyrocystis Lunuu. *Photochemistry and Photobiology* 10, 4 (1969), 227–232.

[43] Sana Sharifian, Ahmad Homaei, Roohullah Hemmati, and Khosro Khajeh. 2017. Light emission miracle in the sea and preeminent applications of bioluminescence in recent new biotechnology. *Journal of Photochemistry and Photobiology B: Biology* 172 (2017), 115 – 128.

[44] Giorgio Soli. 1966. Bioluminescent cycle of photosynthetic dinoflagellates. *Limnology and Oceanography* 11, 3 (1966), 355–363.

[45] David L Spector. 2012. *Dinoflagellates*. Academic Press.

[46] Elijah Swift and Edward G. Durbin. 1972. The phased division and cytological characteristics of Pyrocystis spp. can be used to estimate doubling times of their populations in the sea. *Deep Sea Research and Oceanographic Abstracts* 19, 3 (1972), 189–198.

[47] PB Tett. 1971. The relation between dinoflagellates and the bioluminescence of sea water. *Journal of the Marine Biological Association of the United Kingdom* 51, 1 (1971), 183–206.

[48] Alexander Toet, Menno Henselmans, Marcel P Lucassen, and Theo Gevers. 2011. Emotional effects of dynamic textures. *i-Perception* 2, 9 (2011), 969–991.

[49] Martha Valiadi and Debora Iglesias-Rodriguez. 2013. Understanding bioluminescence in dinoflagellates—how far have we come? *Microorganisms* 1, 1 (2013), 3–25.

[50] Anna Vallgårda, Morten Winther, Nina Mørch, and Edit E Vizer. 2015. Temporal form in interaction design. *International Journal of Design* 9, 3 (2015).

[51] Tim van Dortmont. 2019. *Growing light*. Master's thesis. Delft, The Netherlands.

[52] Peter von Dassow, Rachel N. Bearon, and Michael I. Latz. 2005. Bioluminescent response of the dinoflagellate Lingulodinium polyedrum to developing flow: Tuning of sensitivity and the role of desensitization in controlling a defensive behavior of a planktonic cell. *Limnology and Oceanography* 50, 2 (2005), 607–619.

[53] HH Wang, M Ronnier Luo, P Liu, Y Yang, Z Zheng, and X Liu. 2014. A study of atmosphere perception of dynamic coloured light. *Lighting Research & Technology* 46, 6 (2014), 661–675.

[54] Jennifer Weiler, Piyum Fernando, Nipuni Siyambalapitiya, and Stacey Kuznetsov. 2019. Mycelium artifacts: Exploring shapeable and accessible biofabrication. *DIS 2019 Companion - Companion Publication of the 2019 ACM Designing Interactive Systems Conference* (2019), 69–72.

[55] Thérèse Wilson and J Woodland Hastings. 2013. *Bioluminescence: living lights, lights for living*. Harvard University Press.

[56] Rongpeng Zhang, Carolina Campanella, Sara Aristizabal, Anja Jamrozik, Jie Zhao, Paige Porter, Shaun Ly, and Brent ABauer. 2020. Impacts of Dynamic LED Lighting on the Well-Being and Experience of Office Occupants.*International Journal of Environmental Research and Public Health* 17, 19 (2020), 7217.