"Is this alive?"

Towards a vocabulary for understanding and communicating living material experiences

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"Is this *alive*?": towards a vocabulary for understanding and communicating living material experiences

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Abstract: Living materials are a nascent material class where living organisms are embedded and kept alive in the design outcome to achieve novel functionalities, expressions, and interactions. Experiential characterisation studies with potential end-users will provide insights for developing these novel materials for meaningful material applications. Nevertheless, the current literature lacks a vocabulary to communicate and discuss living materials in user studies. To bridge this gap, our paper presents the development of a "Living Materials Vocabulary" consisting of 45 descriptive items. Through a term frequency analysis of relevant literature and in-depth interviews with eight biodesigners, we identified a set of descriptions which we clustered under five themes: *origin, making, agency and autonomy, temporality, and impact of living materials.* We selected representative items from these themes to compile our final vocabulary. We discuss how our vocabulary can be operationalised in living material characterisation studies and further inspire future biodesign practice.

Keywords: biodesign; living materials; design tools; materials experience

1. Introduction

In biodesign, living organisms are often utilized to achieve sustainable material alternatives and unique expressions in non-living artefacts (Karana et al., 2018; Myers, 2012; Camere & Karana 2018a; Ginsberg et al., 2014; Collet, 2017). Over the last years, design and Human-Computer Interaction (HCI) communities have shown interest in keeping organisms alive in the final biodesign outcome, to lay emphasis on the ability of living organisms to enable unique forms of interactions between humans and artefacts (Karana et al., 2020; Karana et al., 2017; Merritt et al., 2020; Pataranutaporn et al., 2018; Parkers & Dickie, 2013; Pataranutaporn et al., 2020). Merritt et. al. (2020) argued that there is something 'fundamentally different in the way living media can support embodied interaction' unlike non-living media and 'this quality might be due to humans experiencing the shared quality of

being alive' (p. 13). Such unique forms of interactions between living materials and humans can lead to care (Karana et al., 2020), and empathy for artefacts in use (Cheok et.al., 2008). For example, Rafigh (Hamidi & Baljko, 2014), a living media interface, utilizes the care, responsibility, and empathy feelings elicited by living beings (Wilson, 1991) to motivate children involving repetitive and sometimes boring tasks. The well-being of the living organism and its growth facilitates engagement and interest of children as a form of alternative reward mechanism of the interface (Hamidi & Baljko, 2017). In another living artefact, Biogarmentry, the designer Roya Aghighi envisions a photosynthetic living garment that can purify air around the user and illustrates unique living aesthetics as a result of growth and death of habituated algae (Figure 2). This living textile requires people to perform novel care actions different than those for conventional textiles.

Figure 1. Biogarmentry by Roya Aghighi. The color of the textile changes over time as a result of growth and death of the microalgae. The image retrieved from https://www.royaaghighi.com/biogarmentry.html

These two examples among others (see, for an overview, Pataranutaporn et al., 2020, and Karana et al., 2020) show that living materials with their peculiar qualities derived from their livingness, will make us think, feel, and do in different ways than non-living materials. Putting forward this social dimension of living materials central to any biodesign endeavour, Karana et al. (2020) proposed purposeful design of living artefacts by seeking answers for questions like 'how do we live with living artefacts? How do we experience and attend to their livingness?'. Accordingly, the authors suggest that understanding living materials from

an experiential standpoint will help carefully design materials embodied in meaningful applications that are more easily assimilated into everyday life.

Qualities peculiar to livingness are mainly determined by *growth* and *reproduction* in living materials (Gilbert & Ellis, 2019; Nguyen et. al., 2018). Unlike conventional or smart materials, how we experience the temporal changes in living materials, i.e., their living aesthetics (Karana et al., 2020), are highly dependent on these two phenomena, that are largely influenced by the elements of the habitat. Hence, changes on the conditions of the habitat can result in unpredictable *emergent qualities* (Bedau et. al., 2009) in living materials that may not be anticipated by designers. Even though recent work in design and HCI has emphasized such emergent qualities and unique experiences derived from and associated with 'being alive' (Merritt et al., 2020; Mitchell, 2015, Karana et al., 2020; Barati et al., 2021; Ofer et al., 2020; D'Olivo & Karana, 2021), what qualities are peculiar to the ways we define and communicate living materials has not been systematically explored to date.

In this paper, to bridge this gap in the design of living materials, we present the development of a vocabulary set to be used in diverse studies when the aim is to communicate unique qualities of living materials and explore living material-people relationships in biodesign. Specifically, we collected descriptive terms from the literature and interviews with eight biodesigners to obtain a comprehensive list of items concerning living materials. Next, we categorized these items into five main themes: *origin, making, agency and autonomy, temporality, and impact of living materials,* and selected representative items from each theme to convene our final vocabulary. We discuss the implications of this vocabulary set for biodesign.

2. Materials experience and experiential characterizations of materials

In experiential characterization studies, designers explore the ways materials make people think, feel, and act through user studies to facilitate a holistic understanding of material experiences (Karana et al., 2015; Camere & Karana, 2018b; Veelaert, et al., 2020). These studies help designers to identify the potential material experiences, inspire material directions, guide further development of the material, or select an application domain (Camere & Karana, 2018b). Material experiences include four levels, which are *sensorial* (e.g., the material is sensed as smooth, shiny, etc.), *interpretative* (meanings) (e.g., the material is perceived as sexy, modern, etc.), *affective* (emotions) (e.g., the material makes us feel amazed, disgusted, etc.), and *performative* (e.g., the material shapes 'ways of doing and practices') (Giaccardi & Karana, 2015). In the experiential characterization, designers examine the relationships between these four levels.

Krippendorff and Butter (2008) proposed that we need words to discuss and theorize experiences. Words in experiential characterization studies for materials can be used in semantic scales (e.g., antonymous, or bipolar adjectives) to measure to what extent an experiential quality is present or absent for the user, coupled by material representations (e.g., samples, digital models, etc.) (see, for an extensive overview, Veelaert et al., 2020). In 2018, Camere and Karana introduced an experiential characterisation toolkit which proposed a systematic and agile way to evaluate all four experiential levels to facilitate the characterisation of novel and unknown materials or to provide new insights about a known material. The toolkit provides picture sets for the performative and interpretive levels of materials experience, and a vocabulary set for the sensorial, interpretive, and affective levels to support conversations between researchers and participants. The vocabulary set of this toolkit (Figure 3) was developed based on the studies conducted by Karana (2009) with conventional materials (e.g., wood, copper, plastics etc.).

Figure 2. Sensorial, affective, and interpretive vocabulary provided by the experiential characterization toolkit developed by Camera and Karana (2018).

When it comes to exploring experiential qualities of materials from living organisms, current vocabularies used to represent and explore these novel materials do not give justice to the unique qualities of living materials (e.g., growing, alive, regenerative) (D'Olivo & Karana, 2021). Many scholars argue that the words should be carefully selected by considering the risk of negative connotations (Roosth, 2017; McLeod & Nerlich, 2017; D'Olivo & Karana, 2021). Then, when people pose the question, 'Is this alive?', how should these materials be

described? Which vocabulary should be used to communicate and understand the unique experiential qualities of these materials?

3. The present research

We conducted a systematic literature review and interviews with eight biodesigners experienced in designing living artefacts to collect descriptive items, such as nouns and adjectives used for describing living materials in design. The collected articles from the literature review and the transcripts of interviews were used in a term frequency analysis to collect representative descriptive items. Figure 3 shows the general overview of the conducted studies and analysis.

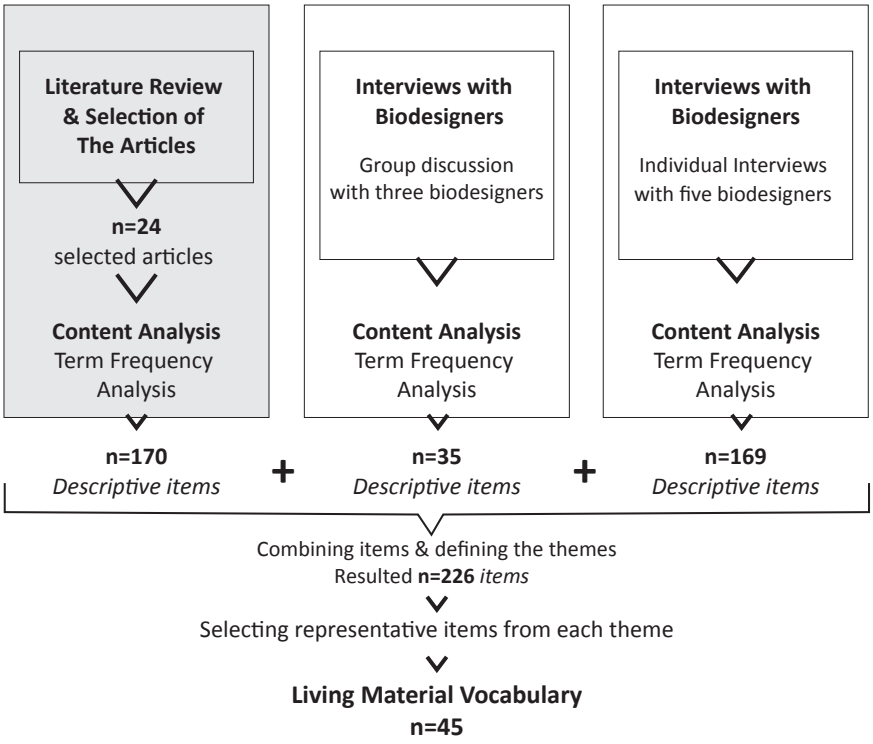


Figure 3. The overview of the research methodology.

3.1 Collecting descriptions from literature

Method

We conducted a literature review across design, materials science, and HCI through online databases. We searched for relevant publications using the following keywords: 'growing design', 'growing materials', 'living materials', 'engineered living materials', 'living interfaces', 'living media', 'living media interfaces', 'living artefacts', and 'hybrid living materials'. We also searched the websites of authors or research groups that investigate living materials for relevant grey literature. This resulted in an initial set of 2593 peer reviewed conference and journal articles. We checked the titles and abstracts of the articles to select those that integrate living organisms into the design of products, interfaces, or

speculative concepts, where organisms are kept alive. In this way, we excluded articles (i) utilizing living organisms for living tissues, and (ii) using the word 'living' as a synonym of interactive/adaptive systems, but not involving actual living organisms in the design. This filtering process resulted in a total of 74 articles. A backward and forward citation analysis of these articles resulted in 40 more articles. From these 114 articles, we eliminated articles on plants and pets that were not integrated into artefacts. Next, we excluded publications presenting the development of living materials from a technical perspective with no potential application scenario or no link to material-people relationships. This left us with a total of 24 articles. Finally, we conducted a term frequency analysis with these 24 articles (Table 1) to finalize our list of descriptive items.

Table 1. The list of articles utilized in the term frequency analysis

Adamatzky et al., 2020	Living wearables from slime mould and fungi
Bader et al., 2016	Grown, printed, and biologically augmented: An additively manufactured microfluidic wearable, functionally templated for synthetic microbes
Cheok et al., 2008	Empathetic living media
Gerber, Kim and Riedel-Kruse, 2016	Interactive Biotechnology: Design Rules for Integrating Biological Matter into Digital Games
Harvey et al., 2014	Innocent Fun or "Microslavery"?: An Ethical Analysis of Biotic Games
Hamidi and Baljko, 2014	Rafigh: A living media interface for learning games
Hamidi and Baljko, 2017	Engaging children using a digital living media system
Karana, Barati and Giaccardi, 2020	Living Artefacts : Conceptualizing Livingness as a Material Quality in Everyday Artefacts
Karana et al., 2019	Alive. Active. Adaptive: Experiential knowledge and emerging materials
Kim and Poslad, 2019	Growable, invisible, connected toys: Twitching towards ubiquitous bacterial computing
Kim et al., 2019	Microbial Integration on Player Experience of Hybrid Bio-digital Games
Kim, Poslad and Van Dierendonck, 2019	Moldy ghosts and yeasty invasions: Glitches in hybrid bio-digital games
Lamers and van Eck, 2012	Why Simulate ? Hybrid Biological-Digital Games
Liu et al., 2018	3D Printing of Living Responsive Materials and Devices
Liu et al., 2017	Stretchable living materials and devices with hydrogel-elastomer hybrids hosting programmed cells
Lee et al., 2015	Trap it! : A playful human-biology interaction for a museum installation.
Merritt et al., 2020	Living media interfaces: a multi-perspective analysis of biological materials for interaction.
Moisy and Pschetz, 2017	Designing with living organisms
Parkes and Dickie, 2013	A Biological Imperative for Interaction Design
Pataranutaporn et al., 2020	Living Bits: Opportunities and Challenges for Integrating Living Microorganisms in Human-Computer Interaction
Pataranutaporn, Ingalls and Finn, 2018	Biological HCI: Towards integrative interfaces between people, computer, and biological materials
Riedel-Kruse et al., 2011	Design, engineering and utility of biotic games
Rivera-Tarazona, Campbell and Ware, 2021	Stimuli-responsive engineered living materials
Smith et al., 2020	Hybrid Living Materials: Digital Design and Fabrication of 3D Multimaterial Structures with Programmable Biohybrid Surfaces

Content analysis

Content analysis is a research method that provides a systematic, objective, and quantitative description of a certain content by counting the occurrences of meaning units, such as words, phrases, content categories, and themes (Kipperdorff, 2004; Werber, 1990; Kassarjian, 1977). Researchers can analyse texts from different perspectives by examining the high-frequency or low-frequency words.

We analysed the selected 24 articles in word frequency analysis with the qualitative analysis software MAXQDA2020 by uploading these articles to the program. First, the program generated a long list resulting in N=12868 items. This list was cleaned by taking out unrelated words, such as conjunctions, prepositions, and author names. For example, the different forms of the verb *to be* (e.g., *is* and *was)*, the articles *a* and *the,* and one- or two-letter words, such as *I* and *we,* were removed from the list. Finally, we checked the terms in their context by screening the sentences in which they were mentioned. If the meaning of

the item was not clear from the sentence, we checked the article to understand if the item was used to describe a living material. In this way, we eliminated the terms such as pheromones, phenylketonuria, which do not refer to qualities of living materials. Also, for example, 'toxic' was mentioned as 'toxic substances', 'toxic compounds' or 'toxic by-products' in the articles and did not refer to living materials. Therefore, we removed this item from the list. We also combined similar words with different suffixes, such as *disgust* and *disgusts* or 'smell' and 'smelling' that appeared as separate entries in the analysis.

After this analysis, we attained a total of N=170 descriptive items.

3.1 Collecting descriptions from interviews with biodesigners

We conducted in-depth interviews with eight biodesigners who actively work and design with living materials derived from algae, bacteria, and fungi that are the most common organisms used by designers (Camere & Karana, 2017). We mainly looked for items different than the ones collected from the literature to expand our list. We selected biodesigners, who each work with different living materials from different species of algae, bacteria, and fungi, to collect various descriptive items for different qualities. We recruited them for their expertise on only one type of living material, even though they have worked with multiple living materials.

In total, we interviewed eight Europe-based biodesigners, of which seven have residency in the Netherlands, and one of them performs biodesign practice in the United Kingdom. All interviews were performed in English. The first three interviews were conducted in a focus group set up, where three biodesigners simultaneously shared their experiences with living materials. This pre-study helped us to improve our method, which we present in the next section. The following five interviews were conducted individually.

Pre-Study: Focus group interviews with three biodesigners

Participants

The purpose of the study was to discern the descriptive items that biodesigners use while communicating living materials. For the selection of experts in this novel design practice, we followed Camera and Karana's (2017) conclusion that these materials require a minimum of one year experience to become familiar with the material to its full extent. Therefore, we invited three biodesigners who were actively engaged in the growth and design of living materials for more than a year and who has experience with three different types of living materials which are bacteria-based, algae-based, and fungi-based.

Procedure

Participants were invited to the study through email. Before the study, we asked biodesigners to send any kind of media representation (e.g., pictures, video, illustrations) of their living material that they use to express the qualities of the material t*o someone who does not know the material*. These representations were placed on an online platform (Miro) together with the study questions and used during the study to stimulate discussions.

The study was conducted in a focus group format where researchers moderate a discussion on a specific topic with a group of individuals to explore issues from the participants' complex personal experiences, perceptions, beliefs, and attitudes (Cornwall and Jewkes, 1995). We employed this technique via a video conference call through the platform ZOOM due to COVID-19 restrictions.

The study was structured in two parts to provide a progressive deepening of the discussion. In the first part of the study, participants wrote their answers for two group of questions on their Miro board. The first group of questions included open-ended questions related to their own material representations to stimulate them to describe the qualities of their living material in detail (Figure 4):

1. How would you describe your material?
2. Which aspects of your material are communicated by the picture/video you shared?
3. Why do you think this picture or video is able to communicate your material?

Figure 4. Examples from participants' Miro board. Left: Representative pictures for mycelium sent by the participant. Right: The same participant's answers to the first group of questions in the study.

For the second group of questions, we utilized the interpretive and affective vocabulary set provided by the experiential characterization toolkit (presented earlier in Section 2) as stimuli to trigger discussions relevant to interpretive and affective levels of experiential

qualities of living materials. First, we asked them to select the descriptive items that fit to their material most. They could also add new items in addition to the given ones. Next, they used the same list to select the items (meanings and emotions) that they would like to ask to users to learn how they would experience the material.

In the second part, participants were asked to share their answers with the group and describe their materials to the other participants. The study took in total of 2,5 hours. The session was audio-recorded and later converted to text with Microsoft Word's dictation feature.

Analysis

The transcript was screened through the qualitative analysis software MAXQDA2020 to uncover descriptive items for living materials. We followed the same procedure presented in Section 3.1 to eliminate irrelevant items. As a result, we acquired N=35 descriptive items.

Individual interviews with biodesigners

In the pre-study, we conducted focus group interviews as it allows the exploration of issues in-depth where there is limited prior research on the topic, and it builds on group dynamics without imposing a conceptual framework (Nyumba et al., 2017). However, we decided to change our method to individual interviews with biodesigners due to the following aspects we experienced in our pre study. We played a peripheral role in the focus group discussion as a 'facilitator' (Bloor et al., 2001) and moderated the discussion between participants by asking questions and controlling the group dynamics. We were not involved in an in-depth discussion with individual participants. Furthermore, we noticed that one designer was relatively silent and biased due to two other designers, who were relatively dominant. This is, in fact, a potential pitfall of focus group studies (Nyumba et al., 2017). Furthermore, we did not have enough time to give equal attention to each material within the given time.

Participants

Similar as in the focus group, we approached biodesign experts who had at least one year of experience working with living materials derived from algae, bacteria, and fungi. We recruited biodesigners for their expertise in one specific type of material. In total, we interviewed five biodesign experts of five different types of living materials.

Procedure

Our procedure was similar to the one used in the previous study. However, to have more time for discussions, we asked participants to answer the study questions before the study that were posted on their Miro board. The interviews were conducted over video calls through the platform ZOOM due to COVID-19 restrictions. In the interview, we first

discussed participants' answers to the open-ended questions and subsequently their selection from the Ma2E4 list and the new items they added.

In the focus group interviews, we observed that participants struggled to suggest new items different from the provided interpretive and affective lists. Hence, to stimulate additional descriptive items, we asked participants three additional questions at the end of the interview.

1. What is the most pleasant quality of the material for you?
2. What is the most disturbing quality of the material for you?
3. What is the unique quality of the material for you?

The audio-recorded interviews lasted approximately one hour. The recordings were subsequently transcribed, and interview transcriptions were used in the term frequency analysis.

Analysis

The interview texts were analysed through the qualitative analysis software MAXQDA2020 as described above. This resulted in N= 2833 different items. After following the same elimination process mentioned in the literature review, a total of N=169 descriptive items were collected. All collected items from both the literature, focus group and individual interviews were combined (N= 226) (Table 2). The descriptive items and emergent themes are discussed in the results section.

Table 2. Descriptive items collected from the term frequency analysis of the literature and interviews.

active	biomaterial	enchantment	hypnotising	non-traditional	self-grow	unprecedented
adaptive	biotic	engaging	impressive	novel	self-healing	unpredictable
advanced	boredom	engineered	incandescent	nurtured	self-organizing	unprocessed
aesthetic	breathable	enjoyable	incorporated	ordinary	self-repairing	unstable
afraid	calming	enjoyment	incubated	pathogenic	self-replicating	unsustainable
agency	care	evolutionary	inhabited	photo-sensitive	self-reproducing	unusual
aggression	changing	excitement	inoculated	photoresponsive	self-reproduction	useful
aliens	co-creation	fabricated	integrated	photosynthetic	self-sustaining	wise
alive	co-design	fascinate	intelligent	playful	sensitive	worry
amazing	collaborating	fear	interactive	pleasant	sexless	yeasty
amusing	collaborator	feminine	interesting	pleasurable	shame	
ancient	color-changing	fragile	irreversible	poisoning	smell	
annoying	comforted	frustration	joyful	predictable	sober	
arresting	confrontational	fully-grown	light-emitting	primitive	sophisticated	
artificial	contemplation	fun	light-responsive	programmed	spatio-temporal	
asexual	cooperated	functional	living	provocative	special	
assemblage	crafted	funny	lovely	provoking	stimuli-driven	
assemble	cultivated	futuristic	manipulated	reactiveness	stimuli-responsive	
attractive	cultured	genetically-engineered	manufactured	regenerative	stylish	
attuned	curiosity	glowing	martian	relaxing	surreal	
autonomous	dangerous	gross	masculine	reluctance	sustainable	
beautiful	decaying	grow	meditative	replicate	synthesized	
bio-based	dependent	grow-ability	melancholy	reproducible	synthetic	
bio-computation	designed	growable	mesmerising	respectable	tailored	
bio-digital	dirty	growing	microbial	responsibility	temporal	
bio-engineering	disappointing	grown	modified	responsive	temporary	
bio-fabrication	disgust	guilt	moisture-responsive	reversible	therapeutic	
bioculture	disgusting	habituated	moldy	revolutionary	time-dependent	
biodegradable	distrust	handcrafted	monster	romantic	time-evolving	
bioengineered	doubt	harmful	motivating	rough	toxicated	
biofabricated	dying	harmless	mouldy	safe	transform	
biohybrid	dynamic	harnessed	mutualistic	satisfaction	transgender	
biological	elegant	healing	mysterious	scary	uncomfortable	
biologically-integrated	embedded	hesitant	natural	seductive	unexpected	
biology-based	empathetic	hybrid	non-intrusive	self-activated	unique	
bioluminescent	empathy	hybrid-living	nostalgic	self-cleaning	unnatural	

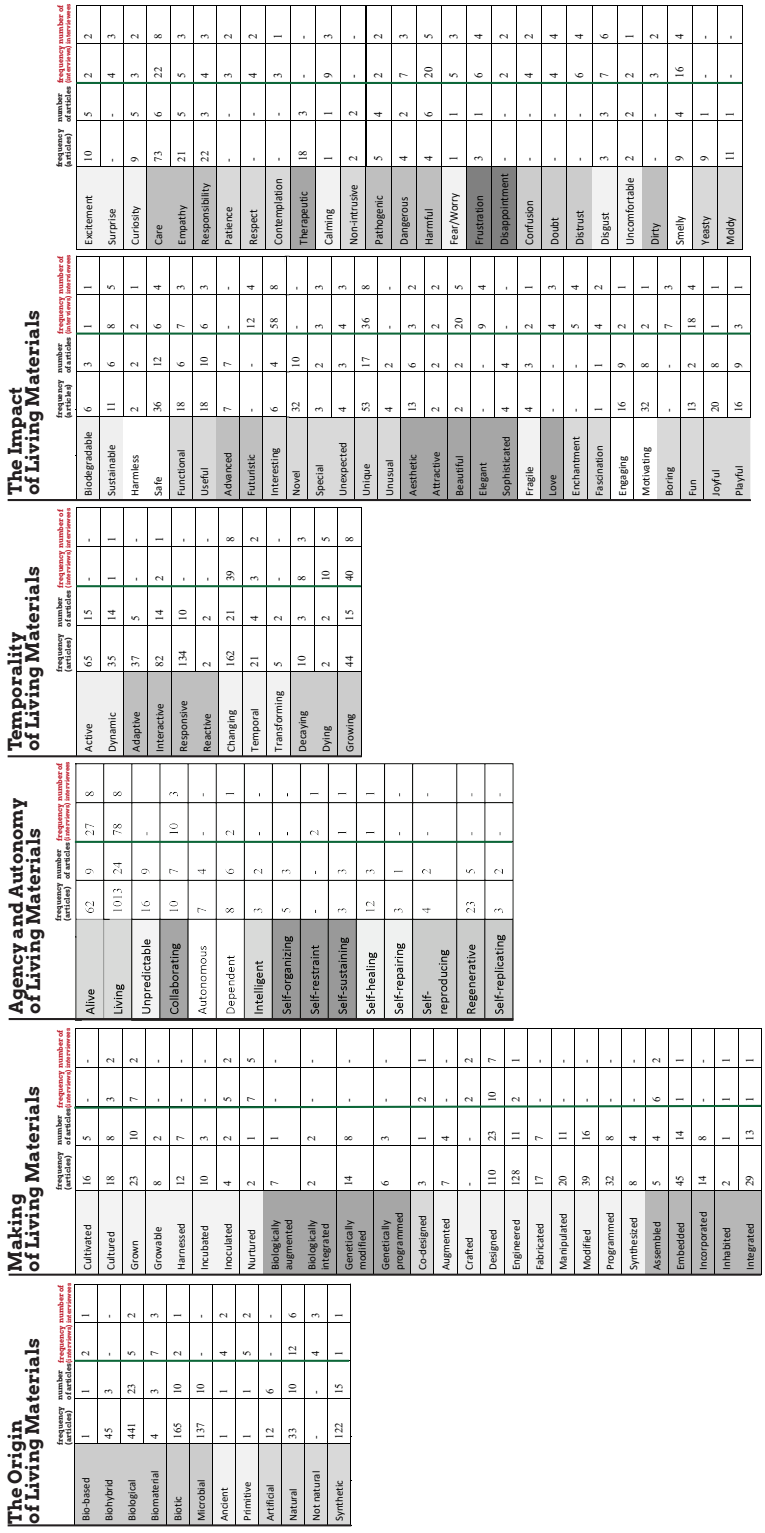
4. Results

4.1 The procedure of selecting representative items

We envisage that researchers and designers will use these descriptive items with laypersons such as in user studies. Hence, we refined our list to provide a clear and understandable list. We eliminated the items that are mentioned only one time. The first author searched for thematically close items (e.g., changing and transforming). With a back-and-forth reading between the items and the context, in which a specific item was presented in the articles and interview transcriptions, the first author identified the initial themes to categorize the relational items (i.e., repeating patterns, Saldana, 2015). Then, these initial themes and their name were discussed by the research team until agreement was reached. Finally, five main themes were identified: *Origin*, *Making*, *Agency and Autonomy, Temporality, and Impact of living materials* (presented in Section 4.2).

After grouping the descriptive items under these five themes, we identified subgroups under each theme based on the similarities between the items. For example, under the Agency and Autonomy theme, we created a subgroup from the items: 'self-healing' and 'self-repair' that refer to their ability to retrieve their original or natural state after a damaging loss or injury process. Table 3 presents the final grouping of the selected items under five themes, and their subgroups.

Table 3. Descriptive items collected from the term frequency analysis of the literature and interviews. Subgroups are shown with the tones of grey.



The Origin of Living Materials				
	frequency (verbatim)	number of articles	frequency number of references
Bio-based	1	1	2	1
Biohybrid	45	3	-	-
Biological	441	23	5	2
Biomaterial	4	3	7	3
Biotic	165	10	2	1
Microbial	137	10	-	-
Ancient	1	1	4	2
Primitive	1	1	5	2
Artificial	12	6	-	-
Natural	33	10	12	6
Not natural	-	-	4	3
Synthetic	122	15	1	1

Making of Living Materials				
	frequency (verbatim)	number of articles	frequency number of references
Cultivated	16	5	-	-
Cultured	18	8	3	2
Grown	23	10	7	2
Growable	8	2	-	-
Harnessed	12	7	-	-
Incubated	10	3	-	-
Inoculated	4	2	5	2
Nurtured	2	1	7	5
Biologically augmented	7	1	-	-
Biologically integrated	2	2	-	-
Genetically modified	14	8	-	-
Genetically programmed	6	3	-	-
Co-designed	3	1	2	1
Augmented	7	4	-	-
Crafted	-	-	2	2
Designed	110	23	10	7
Engineered	128	11	2	1
Fabricated	17	7	-	-
Manipulated	20	11	-	-
Modified	39	16	-	-
Programmed	32	8	-	-
Synthesized	8	4	-	-
Assembled	5	4	6	2
Embedded	45	14	1	1
Incorporated	14	8	-	-
Inhabited	2	1	1	1
Integrated	29	13	1	1

Agency and Autonomy of Living Materials				
	frequency (verbatim)	number of articles	frequency number of references
Alive	62	9	27	8
Living	1013	24	78	8
Unpredictable	16	9	-	
Collaborating	10	7	10	3
Autonomous	7	4	-	-
Dependent	8	6	2	1
Intelligent	3	2	-	-
Self-organizing	5	3	-	-
Self-restraint	-	-	2	1
Self-sustaining	3	3	1	1
Self-healing	12	3	1	1
Self-repairing	3	1	-	-
Self-reproducing	4	2	-	-
Regenerative	23	5	-	-
Self-replicating	3	2	-	-

Temporality of Living Materials				
	frequency (verbatim)	number of articles	frequency number of references
Active	65	15	-	-
Dynamic	35	14	1	1
Adaptive	37	5	-	-
Interactive	82	14	2	1
Responsive	134	10	-	-
Reactive	2	2	-	-
Changing	162	21	39	8
Temporal	21	4	3	2
Transforming	5	2	-	-
Decaying	10	3	8	3
Dying	2	2	10	5
Growing	44	15	40	8

The Impact of Living Materials				
	frequency (verbatim)	number of articles	frequency number of references
Biodegradable	6	3	1	1
Sustainable	11	6	8	5
Harmless	2	2	2	1
Safe	36	12	6	4
Functional	18	6	7	3
Useful	18	10	6	3
Advanced	7	7	-	-
Futuristic	-	-	12	4
Interesting	6	4	58	8
Novel	32	10	-	-
Special	3	2	3	3
Unexpected	4	3	4	3
Unique	53	17	36	8
Unusual	4	2	-	-
Aesthetic	13	6	3	2
Attractive	2	2	2	2
Beautiful	2	2	20	5
Elegant	-	-	9	4
Sophisticated	4	4	-	-
Fragile	4	3	2	1
Love	-	-	4	3
Enchantment	-	-	5	4
Fascination	1	1	4	2
Engaging	16	9	2	1
Motivating	32	8	2	1
Boring	-	-	7	3
Fun	13	2	18	4
Joyful	20	8	1	1
Playful	16	9	3	1
Excitement	10	5	2	2
Surprise	-	-	4	3
Curiosity	9	5	3	2
Care	73	6	22	8
Empathy	21	5	5	3
Responsibility	22	3	4	3
Patience	-	-	3	2
Respect	-	-	4	2
Contemplation	-	-	3	1
Therapeutic	18	3	-	-
Calming	1	1	9	3
Non-intrusive	2	2	-	-
Pathogenic	5	4	2	2
Dangerous	4	2	7	3
Harmful	4	6	20	5
Fear/Worry	1	1	5	3
Frustration	3	1	6	4
Disappointment	-	-	2	2
Confusion	-	-	4	2
Doubt	-	-	4	4
Distrust	-	-	6	4
Disgust	3	3	7	6
Uncomfortable	2	2	2	1
Dirty	-	-	3	2
Smelly	9	4	16	4
Yeasty	9	1	-	-
Moldy	11	1	-	-

To cover all aspects of living materials, we selected at least one descriptive item from each subgroup as the representative item of that subgroup. To select the most relevant descriptive items under a theme or subcategory, we used the following criteria:

1. The item that has the highest frequency of mention in articles
2. The item that has the highest frequency of mention in interviews
3. The items that are mentioned in multiple articles
4. The items that are mentioned by multiple interviewees
5. The items that were mentioned both in articles and interviews

We first checked for each descriptive item whether the criteria listed above were fulfilled and we noted the number of complied criteria by each item. Next, we selected the descriptive items from each sub-group that meets more criteria than the other items. For example, 'living' is the descriptive item that meets more criteria than the other items in this sub-group. Therefore, we included it in our final set of vocabulary. Finally, we discussed the familiarity of a selected item among the authors. For example, if an item was considered as jargon, we changed the item with a more familiar word. If more than one item in a subgroup fulfills multiple criteria, we gave priority to the items that particularly meet the criteria 4 and 5. In some cases, there were individual items close enough to be categorised under a subgroup, yet still have slightly different connotations (e.g., growing, dying, and decaying, are all related to the life cycle but refer to different stages of life). In this case, we selected all items with different meanings from that subgroup to cover all representative items for unique qualities in the final list. Table 4 illustrates our selection process applied for one of the subgroups which also includes items with different meanings.

Table 4. The selection criteria and the selection process that is applied to the subgroup located in the origin of the living materials theme. After defining the complied criteria by each item, we selected two items: 'natural' and 'synthetic' from this sub-group.

Natural	29	9	12	6
Not natural	-		4	3
Artificial	12	6	-	-
Synthetic	118	14	1	1

(1) The item that has the highest frequency of mention in articles
(2) The item that has the highest frequency of mention in interviews
(3) The items that are mentioned in multiple articles
(4) The items that are mentioned by multiple interviewees
(5) The items that were mentioned both in articles and interviews

Through the selection procedure mentioned above, N=45 descriptive items were selected as representative vocabulary of the five main themes presented below. This final set of vocabulary, Living Materials Vocabulary, is presented in Table 5.

4.2 Five themes to categorize unique qualities of living materials

The origin of living materials

This theme consists of descriptive items that refer to the origin of living materials, i.e., the descriptions explicitly refer to biological origin of the living materials and the original habitat in which a living organism thrives (D'Olivo and Karana, 2021). While defining living materials, their origin is indicated with terms, such as '*biological*'. We also included items such as '*natural*', '*synthetic*', 'primitive', that refer to the quality of the resource the material is made of. In the interviews, one of participants referred to the origin of the material as follows:

> 'The material is natural, but if you only show mycelium, then people think what is this material like a kind of Styrofoam. But if you show a mushroom coming out of it they understand it… I say 'hey, it is mushroom…This is what they do in the nature'.

The making of living materials

The second theme refers to the way living materials are developed. We identified terms specific to novel production ways related to the aliveness and grow-ability of the living materials, such as 'cultured', 'cultivated', 'nurtured', 'grown', or 'genetically modified'. In the interviews, designers also mentioned the novel making process of living materials, which are required to be *'nurtured*' to thrive or function and the involvement of the living organism into this process (Camera & Karana, 2017) that results 'co-designed' outcomes.

The agency and autonomy of living materials

In this category, we present material qualities transpired by two linked but different notions: agency and autonomy of living materials*. Material's agency* refers to the capacity of the living material to affect the environment actively in various ways regarding a variety of goals. M*aterial's autonomy* refers to the ability of the living material to maintain itself over time and resist diverse external and internal perturbations (Moreno and Mossio, 2015). The collected items, such as 'self-healing', 'self-replicating', and self-sustaining' that imply the ability of controling its own affairs and govern itself over time placed under this category. In the interviews, designers also mentioned the agency and autonomy of living materials while designing with them: "*there is no absolute control.", "you do not know everything about them".*

Temporality of living materials

This theme comprises of items, such as ‘dynamic’, ‘interactive’, and ‘changing’ that refer to the temporality of living materials transpired by two biological phenomena inherent to living organisms —namely *growth* and *reproduction.* Hence, we also added the items ‘growing’, ‘dying’ and ‘decaying’. Temporal qualities of living materials were prominent in the interviews. One of the designers mentioned two distinctively different states of mycelium over time that are being wet and soft at the beginning and dry and styrofoam-like later. Another designer mentioned how the bacteria-based material she works with can change and become a totally different material the next day.

> “You start to see the color change with organism’s growth and decay until eventually everything is death.”

The impact of living materials

In this theme, we included the items that refer to the impact of living materials on nature (e.g., biodegradable, sustainable) and on people (e.g., emotions elicited by living materials). In the interviews, it became prominent that designers were concerned that these materials would elicit detrimental meanings, such as ‘dangerous’, pathogenic’, and ‘dirty’ due to the negative connotations of habituated living microorganisms in these materials:

> “…one of the questions ..(from people) ‘it is dangerous, right?’. Because there's such a connotation about fungi killing people... It is nothing to be dangerous, but people are scared of it... It is associated with mould.”

The items describing living aesthetics of these materials, such as ‘glowing’, ‘translucent’ or ‘yeasty’, were also included in this category.

> “...I had it (bioluminescent bacteria) next to my bed; when lights are off, it glows... It is like looking at the Milky Way… it just makes these beautiful swirls of life. It is just amazing and meditative. It is like a lava lamp but better because it is natural. It is hypnotising.”

As explained in Section 4.1, based on the selection criteria, we selected 45 items (Table 5) from the five themes presented above.

Table 5. Living Materials Vocabulary that includes descriptive items representing five themes mentioned in Section 4.2 that refer to different unique qualities of living materials.

advanced	dynamic	love
autonomous	empathy	motivating
beautiful	engineered	natural
biological	exciting	primitive
boring	fascinating	respect
care	fear	responsibility
changing	fragile	safe
co-designed	frustratinig	self-healing
collaborating	fun	self-replicating
confusing	functional	self-sustaining
decaying	growing	smelly
dependent	harmful	sustainable
dirty	intelligent	synthetic
disgusting	interactive	unique
dying	living	unpredictable

5. Discussion

We believe that the deliberate exploration of living material experiences is essential for harnessing the full potential of living materials and fostering living artefacts that are socially embedded into everyday life. To discuss and theorize experiences, we need words (Krippendorff and Butter, 2008), and current definitions and terminologies have been limiting to represent and explore emerging novel materials in the field of biodesign (D'Olivo and Karana, 2021). In this paper, we presented the development of a vocabulary set to inform biodesign research and practice for understanding and communicating unique qualities of living materials in design. In this section, we demonstrate two possible ways this vocabulary can be used in future studies by designers and design researchers and discuss the limitation of our study.

5.1 Two possible scenarios for the living vocabulary use

The presented set of descriptive items can be operationalized in multiple ways to communicate and understand the unique qualities of living materials by researchers and designers. For example, they can be implemented in user studies presented in scales to be rated, or individually to inspire discussions. In Figure 5 we present an example of how these items could be utilized in a questionnaire format in user studies.

Depending on the purpose of the study, the presented vocabulary for living materials can be operationalised partially by including relevant items based on the organism at hand or the specific interest of the designer about a particular theme. For example, a designer might want to use items related to temporality only (changing, dynamic, interactive, growing,

dying and decaying). Our vocabulary should also be considered an organic one that can be extended with items specific to an organism (e.g., glowing, translucent).

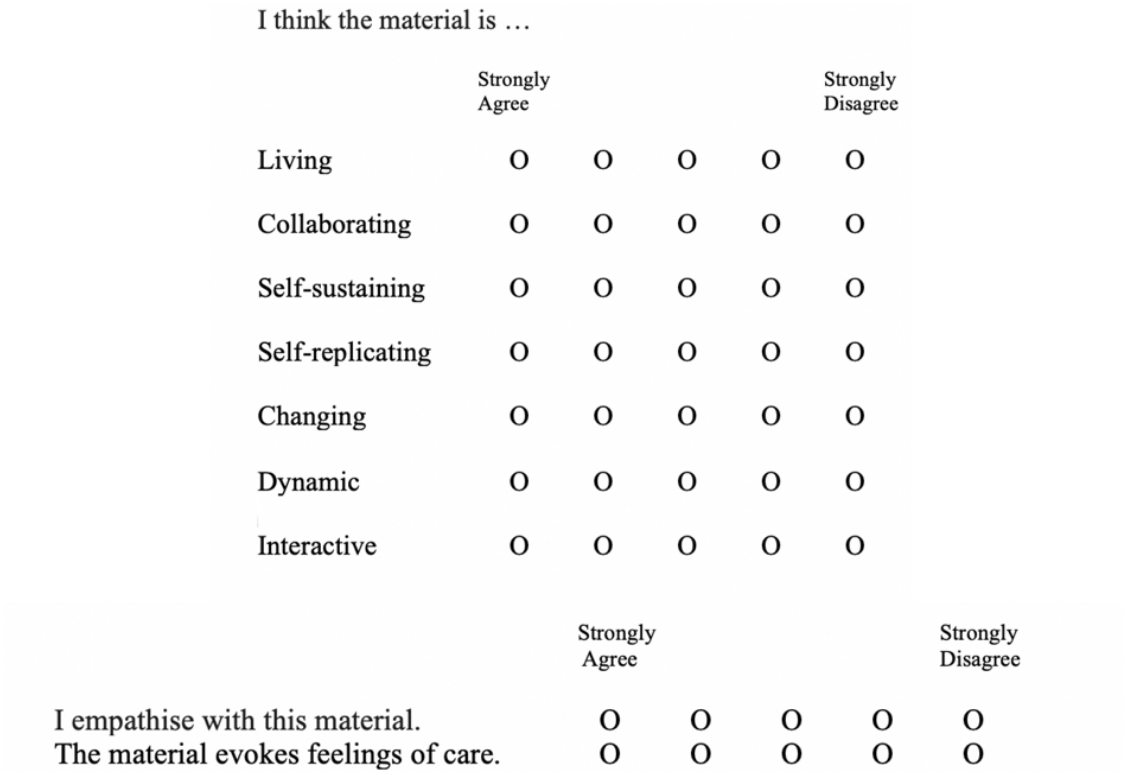


Figure 5. An example of how the set of descriptive items can be operationalised in an experiential characterization study.

Besides the questionnaire format, designers can utilize descriptive items to stimulate design ideation or speculate about future living scenarios with living materials. For example, in a recent workshop we conducted in collaboration with the storytelling expert Sarah Lugthart from Caradt, we implemented the living vocabulary into a card deck designed by the Affect Lab, to discuss possible futures for living with living materials (Figure 6). During the workshop, participants selected four items from different categories and used those qualities in a world-building exercise (Wolf, 2012). The living vocabulary firstly helped participants to understand 'what a living material is' by introducing the qualities and secondly stimulated participants' imagination to create radical futures integrating living materials. We aim to present the details of this workshop and elaborate on the benefits of our vocabulary in the next publication.

Figure 6. "Miraculous Futures for Living Materials" speculative storytelling card deck by Affect Lab (2021). This card deck is designed by incorporating the Living Materials Vocabulary and the themes mentioned section 4.2.

5.2 Limitations of the study

Living materials is a newly emergent material class that requires highly technical skills, specialized equipment, and facility. Therefore, there are not many biodesigners who are experienced in designing living materials. This hindered the process of finding interviewees in our study.

We categorized the collected items under five discrete themes to support our selection process. However, the items in different themes are strongly interrelated. For example, in the interviews, all designers mentioned the *'agency'* and constantly *'changing'* nature of living materials in the making process of living materials. These qualities make the living materials '*unpredictable'* and evokes feelings of '*surprise'* and '*amazement'* but not having absolute control over the result sometimes induces also '*frustration'* and '*disappointment'* when the result is unwanted. Furthermore, we are aware that some items can be positioned under multiple categories. For example, '*primitive'* is placed under the 'Origin' theme, yet it can also refer to how we interpret this material, like '*futuristic*' (i.e., the impact theme). Therefore, this initial taxonomy should be considered a continuum of descriptions to help operationalize our initial selection rather than a strict division.

6. Conclusion

This paper presented a review of how unique qualities of living materials have been expressed by scholars and biodesign experts. In this review, we identified five themes presenting unique qualities of living materials: *origin, making, agency and autonomy, temporality, and impact of living materials.* Based on our analysis, we introduced a Living Materials Vocabulary to be utilized in communication and exploration for experiential

qualities of living materials in biodesign. This final set of 45 descriptive items is proposed to be used in diverse studies, including interviews, questionnaires, focus groups, workshops, and creative sessions by researchers and designers. We hope our work will inspire biodesign communities to further explore the ways these materials can be communicated and discussed towards new avenues for the design of novel living materials.

7. References

Barati, B., Karana, E., Pont, S., & Van Dortmont, T. (2021). Living Light Interfaces - An Exploration of Bioluminescence Aesthetics. DIS 2021 - Proceedings of the 2021 ACM Designing Interactive Systems Conference: Nowhere and Everywhere, 1215–1229. https://doi.org/10.1145/3461778.3462038

Bedau, M. A., McCaskill, J. S., Packard, N. H., & Rasmussen, S. (2010). Living technology: Exploiting life's principles in technology. Artificial Life, 16(1), 89–97. https://doi.org/10.1162/artl.2009.16.1.16103

Bloor, M., Frankland, J., Thomas, M., & Robson, K. (2001). Focus groups in social research. SAGE Publications Ltd.

Camera, S., & Karana, E. (2018). Experiential Characterization of Materials: toward a toolkit. DRS Biennial Conference Series, 4, 25–28. https://doi.org/10.21606/DRS.2018.508

Camere, S., & Karana, E. (2017). Growing materials for product design. Alive. Active. Adaptive: International Conference on Experiential Knowledge and Emerging Materials, EKSIG 2017, 101–115. TU Delft Open.

Cheok, A. D., Kok, R. T., Tan, C., Fernando, O. N. N., Merritt, T., & Sen, J. Y. P. (2008). Empathetic living media. Proceedings of the Conference on Designing Interactive Systems: Processes, Practices, Methods, and Techniques, DIS, 465–473. https://doi.org/10.1145/1394445.1394495

Collet, C. (2017). "Grow-made" textiles. Alive. Active. Adaptive: International Conference on Experiential Knowledge and Emerging Materials, EKSIG 2017, 24–37. TU Delft Open.

D'Olivo, P., & Karana, E. (2021). Materials Framing: A Case Study of Biodesign Companies' Web Communications. She Ji: The Journal of Design, Economics, and Innovation, 7(3), 403–434. https://doi.org/10.1016/J.SHEJI.2021.03.002

Giaccardi, E., & Karana, E. (2015). Foundations of materials experience: An approach for HCI. Conference on Human Factors in Computing Systems - Proceedings, 2015-April, 2447–2456. https://doi.org/10.1145/2702123.2702337

Gilbert, C., & Ellis, T. (2018). Biological Engineered Living Materials: Growing Functional Materials with Genetically Programmable Properties. ACS Synthetic Biology, 8(1), 1–15. https://doi.org/10.1021/ACSSYNBIO.8B00423

Ginsberg, A. D., Calvert, J., Schyfter, P., Elfick, A., & Endy, D. (2014). Synthetic aesthetics:

investigating synthetic biologys designs on nature. Cambridge, MA: MIT Press

Hamidi, F., & Baljko, M. (2014). Rafigh: A living media interface for learning games. Conference on Human Factors in Computing Systems - Proceedings, 407–410. https://doi.org/10.1145/2559206.2574772

Hamidi, F., & Baljko, M. (2017). Engaging children using a digital living media system. DIS 2017 - Proceedings of the 2017 ACM Conference on Designing Interactive Systems, 711–723. https://doi.org/10.1145/3064663.3064708

Karana, E. (2009). Meanings of Materials. Retrieved from https://repository.tudelft.nl/islandora/object/uuid%3A092da92d-437c-47b7-a2f1-b49c93cf2b1e

Karana, E., Barati, B., Rognoli, V., & Zeeuw van der Laan, A. (2015). Material Driven Design (MDD): A Method to Design for Material Experiences. International Journal of Design, 19(2)2015. Retrieved from https://repository.tudelft.nl/islandora/object/uuid%3A7359026d-57f5-4f63-9835-126c5d23baed

Karana, Elvin, Barati, B., & Giaccardi, E. (2020). Living artefacts: Conceptualizing livingness as a material quality in everyday artefacts. International Journal of Design, 14(3), 37–53.

Karana, Elvin, Blauwhoff, D., Hultink, E. J., & Camere, S. (2018). When the material grows: A case study on designing (with) mycelium-based materials. International Journal of Design, 12(2), 119–136.

Kassarjian, H. H. (1977). Content Analysis in Consumer Research. Journal of Consumer Research, 4(1), 8–18. https://doi.org/10.1086/208674

Kim, R., Poslad, S., & Van Dierendonck, R. (2019). Moldy ghosts and yeasty invasions: Glitches in hybrid bio-digital games. Conference on Human Factors in Computing Systems - Proceedings, 1–6. https://doi.org/10.1145/3290607.3312895

Krippendorff, K., & Butter, R. (2008). SEMANTICS: MEANINGS AND CONTEXTS OF ARTIFACTS. Product Experience, 353–376. https://doi.org/10.1016/B978-008045089-6.50017-4

Lee, S. A., Bumbacher, E., Chung, A. M., Cira, N., Walker, B., Park, J. Y., … Riedel-Kruse, I. H. (2015). Trap it! : A Playful Human-Biology Interaction for a Museum Installation. Dl.Acm.Org, 2015-April, 2593–2602. https://doi.org/10.1145/2702123.2702220

Merritt, T., Hamidi, F., Alistar, M., & DeMenezes, M. (2020). Living media interfaces: a multi-perspective analysis of biological materials for interaction. Digital Creativity, 31(1), 1–21. https://doi.org/10.1080/14626268.2019.1707231

Mitchell, R. (2010). Bioart and the vitality of Media. University of Washington Press.

Moreno, A., & Mossio, M. (2015). Biological autonomy: A philosophical and theoretical enquiry. Springer.

Myers, W. (2012). BioDesign: Nature, Science, Creativity. New York: Moma.

Nguyen, P. Q., Courchesne, N. M. D., Duraj-Thatte, A., Praveschotinunt, P., & Joshi, N. S. (2018, May 10). Engineered Living Materials: Prospects and Challenges for Using Biological Systems to Direct the Assembly of Smart Materials. Advanced Materials, Vol. 30. https://doi.org/10.1002/adma.201704847

Ofer, N., Bell, F., & Alistar, M. (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

Parkes, A., & Dickie, C. (2013). A Biological Imperative for Interaction Design. Conference on Human Factors in Computing Systems - Proceedings, 2013-April, 2209–2218. https://doi.org/10.1145/2468356.2468742

Pataranutaporn, P., Ingalls, T., & Finn, E. (2018). Biological HCI: Towards integrative interfaces between people, computer, and biological materials. Conference on Human Factors in Computing Systems - Proceedings, 2018-April. https://doi.org/10.1145/3170427.3188662

Pataranutaporn, P., Vujic, A., Kong, D. S., Maes, P., & Sra, M. (2020). Living Bits: Opportunities and Challenges for Integrating Living Microorganisms in Human-Computer Interaction. PervasiveHealth: Pervasive Computing Technologies for Healthcare. https://doi.org/10.1145/3384657.3384783

Roosth, S. (2017). Synthetic: How life got made. The University of Chicago Press.

Saldana, J. (2015). The coding manual for qualitative researchers. SAGE.

Veelaert, L., Du Bois, E., Moons, I., & Karana, E. (2020). Experiential characterization of materials in product design: A literature review. Materials and Design, 190, 16. https://doi.org/10.1016/J.MATDES.2020.108543

Weber, R. (1990). Basic content analysis (2nd ed.). SAGE Publications, Inc.

Wolf, M. J. P. (2012). Building imaginary worlds : the theory and history of subcreation. 394.

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