StrC–Rich Prospect Taxonomy on Structural Colour: A Tool for Research to Connect Scientific Knowledge on Nature and Biomimetic Design Innovation

by

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Abstract

This research project investigated the nature of colour from a *biocentered* and *biomimetic* perspective. *Biomimicry* or *biomimetics* (from *bios*, meaning life, and *mimesis*, meaning to imitate) is an emerging multidisciplinary field and a new methodology that offers successful and time-tested models of design rooted in life principles. Biomimicry draws on nature's "best ideas" and then emulates them to address human problems approached from a design criterion—critical, project-based, and process-driven.

The phenomenon of structural colour—often described in physics as light interference produced in material surfaces at the nano-scale—is of particular interest in the field of biomimicry, as new discoveries are emerging with potential applications for researchers in biological science and design. Through the scientific and technological literature available, this research project studied the mechanisms of structural colour in life forms, the ways these mechanisms and structures are combined to create colour, the strategies implemented by several species when using them, and the implications for biomimetic implementation on materials and products.

The main objective of this research project was to investigate a way to bridge scientific knowledge and potential biomimetic design applications. Existing gaps in communication between scientific and design disciplines may create limitations in accessing and understanding available scientific data from a design perspective. Such limitations occur due to the different epistemological views of science and design disciplines. It is important to ensure that reliable information is easily accessible and can be understood by people from different fields. The best way to create that kind of situation is to approach it as an issue of facilitation and mediation. An appropriate tool could potentially help to mitigate existing limitations; however, there may

be other intrinsic reasons for these limitations, and some of these reasons that may prevent the communication gaps to be resolved. Focused on such challenges, this research project addresses a two-part correlated research question: How can a biocentered design approach to colour help bridge gaps between scientific knowledge and biomimetic design practices? How can available scientific information/knowledge on structural colour be better organized and more accessible to bridge such gaps?

This research proposes to bridge the gap between scientific knowledge and potential biomimetic design applications through the creation of an ecosystem of dynamic digital tools. These tools, inspired by the Academic Prototyping method and the Rich-Prospect Browsing concept, test ways of accessing available scientific knowledge about structural colour. The ultimate intention is to improve communication between scientists and designers involved in current biomimetic projects, as well as inspire new projects. This approach invites exploration and addresses what else can be learned or is waiting to be discovered from nature that will help create, manipulate, and use colour without pigments. This project also explores specific ways in which this knowledge can be shared effectively with a broader audience interested in the subject. As an underlying matter, this project may contribute to building upon a biocentered design theory that enables design disciplines to evolve from unsustainable anthropocentric practices. Results of this research provide evidence that the StrC tool has the potential to support designers and scientists, and this research addresses the research questions, and reveals new questions and elements for further discussion, as well as guidance for future steps of the project.

Preface

This dissertation is an original work by Carlos Fiorentino. The research project, of which this dissertation is a part, received research ethics approval from the University of Alberta Research Ethics Board, Project name "STRC: A TOOL FOR RESEARCH TO CONNECT NATURE AND DESIGN," No. Pro00085144, TUESDAY, NOVEMBER 27, 2018.

Part of the scientific examples used for the research conducted for this dissertation was a collaboration of Dr. Tomislav Terzin and his science students at the Augustana Campus, University of Alberta. The digital interface created for the study was designed by Carlos Fiorentino, with the assistance of Computing Science students from University of Alberta. The findings, data analysis, and conclusions in Chapters 5 and 6 are original work, as are the methodology investigation in Chapter 3 and literature review in Chapter 2.

The concepts discussed in Chapter 2—anthropocentrism, biocentrism, sustainability, and biocentred design—were published as the following:

Fiorentino, C. (2016). Escaping the design dystopia: Propositional bio-informed theories to evolve from anthropocentric design. *The International Journal of Sustainability Education*, *12*(3), 15-27. doi:10.18848/2325-1212/CGP

Fiorentino, C. (2018, January). *What is more sustainable than nature? Anthropocentric and biocentered design*. Paper presented at the Fourteenth International Conference on Environmental, Cultural, Economic & Social Sustainability, The Cairns Institute, James Cook University, Australia.

Fiorentino, C. (2018, August). *Transición del Antropocentrismo al Biocentrismo: El Presente Distopico y el Futuro del Diseño*. Paper presented at the IX Congreso Latinoamericano de Enseñanza del Diseño, Congreso de Enseñanza del Diseño Universidad de Palermo, Buenos Aires, Argentina.

The work described in Chapter 4 of this dissertation (design and development of the StrC) was disseminated as the following:

Fiorentino, C., Bissonnette, A., Strickfaden, M., & Terzin, T. (2015, November). *Biomimetics of colour*. Presentation at the Doctoral Colloquim, IASDR Interplay Conference, Brisbane, Australia.

Fiorentino, C., Bissonnette, A., Strickfaden, M., & Terzin, T. (2017, March). *A dynamic taxonomy on structural colour*. Poster presented at the 11th International Conference on Design Principles & Practices, Institute Without Boundaries, Toronto.

Fiorentino, C., Bissonnette, A., Strickfaden, M., & Terzin, T. (2017, March 17). *DTSC: A case of academic prototyping*. Poster presented at the ALES Graduate Research Symposium, University of Alberta.

Fiorentino, C., Bissonnette, A., Strickfaden, M., & Terzin, T. (2019, January). *StrC: A rich-prospect taxonomic interface*. Poster presented at the 15th International Conference on Environmental, Cultural, Economic & Social Sustainability, University of British Columbia, Vancouver.

Fiorentino, C., Terzin, T., Bissonnette, A., & Strickfaden, M. (2019, January 31). *Structural colour*. Presentation at the Biomimicry Alberta Lecture Series, RoundHouse, MacEwan University.

Fiorentino, C., Terzin, T., Bissonnette, A., & Strickfaden, M. (2019, March 7). *Sustainable colours*. Poster presented at the R.E. Peter Biology Conference 2019, University of Alberta.

Fiorentino, C., Terzin, T., Bissonnette, A., & Strickfaden, M. (2019, March 13). *StrC sustainable colours*. Presentation of doctoral research at the ALES Graduate Research Symposium, University of Alberta.

The results and findings of the StrC study described in Chapter 5 were presented as the following:

Fiorentino, C., Terzin, T., Nychka, J., Bissonnette, A., & Strickfaden, M., (2019, June). *StrC: A research tool to connect scientific knowledge of nature with biomimetic design innovation*. Presentation at the International Conference on Nature Inspired Surface Engineering (NISE-2019),Wesley J. Howe Center at the Stevens Institute of Technology, Hoboken, NJ.

I have worked as a design practitioner and graduate researcher on a number of rich-prospect browsing interfaces and academic prototyping projects for more than 10 years. In these endeavours, I was heavily influenced by the digital humanities field. Such projects involved iterations with multiple disciplinary realms, experimenting with diverse methods, and creating a variety of unconventional research tools to solve complex visualization problems. All the original design work applied to the StrC and described in this dissertation benefitted from this experience. Teaching the subject of information design for several years in design courses at the

University of Alberta and Grant MacEwan University has also helped me to learn and reflect on the importance of making information visible and accessible. Lastly, the subject matters of my graduate work (my Master's degree in Design and my PhD studies in Human Ecology), design for sustainability, biomimicry, and biocentered design thinking have shaped my philosophical and epistemological views and interests, encompassed by my teaching and academic writing on the subjects.

My interest in inspiring/informing design from nature started during my master's studies research, when I worked on incorporating sustainability into the design curricula (2006–2008), and later taught the subject to undergraduate design and human ecology students (2010–2015). Back then I made an important discovery: among the most truly ecological approaches to critically thinking about and consciously applying sustainable design (a claim that is discussed in this dissertation's literature review), I discover *biomimicry.* Biomimicry is an emergent discipline that proposes a methodology for learning from nature its most innovative "design solutions," and applies them to solve human problems by design that otherwise would be only approached anthropocentrically. I pose a recurrent question in my lectures and presentations when I introduce the subject of biomimicry to design students and colleagues: "What Is More Sustainable Than Nature?"[1] Notwithstanding how naïve the question might sound, it suggests that sustainability is *built-in* to the concept of biomimicry, and this concept will be discussed in-depth as one of the philosophical foundations of this dissertation.

Uncertainty, and eventual life–academia–career imbalances, might have influenced this doctoral process at times; however, as in nature, an imbalance can be an entropic force that leads

[1] I made this question formal when it became the title of one of my lectures—*What is more sustainable than nature? Anthropocentric and biocentered design*—delivered at the Fourteenth International Conference on Environmental, Cultural, Economic & Social Sustainability, January 2018, The Cairns Institute, James Cook University, Australia.

to creativity and evolution, in this case for ideas and reflections. I have found this approach beneficial, and the result was a resilient 6-year-long process. For a researcher who sees nature as a mentor and adaptation as a narrative, there is a lesson to learn from nature: Resilience is about preparing yourself for embracing uncertainty and change. Paraphrasing Voltaire, uncertainty is an uncomfortable position, but certainty is an absurd one.

Future outcomes of this work may be uncertain, but that is a reason I embarked on this project.

Acknowledgements

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I am grateful to many people for their generous support during all these years of my doctoral project. I would like to express special gratitude to my supervisors, Dr. Megan Strickfaden and Dr. Anne Bissonnette, for their patience, guidance, creativity, and always positive approach, particularly in difficult times. I also would like to thank Dr. Tomislav Terzin, for his open mind, scientific contributions to my work, and inspiring input from the beginning of this process.

It seems impossible to thank all of the individuals who influenced this scholarship, all of the scholars, academics, colleagues and graduates I met during these years at Human Ecology, Art and Design, Computing Sciences, Biological Sciences, Engineering and Physics; and supporting staff from the Faculty of Agricultural, Life & Environmental Sciences (ALES) and Faculty of Graduate Studies and Research (FGSR). To all, thank you.

I also would like to thank the scientists from the international community working on structural colour research, who believed in this project, beyond natural skepticism, from the beginning to the end (DTSC to StrC); colleague designers and friends from the biomimicry international community who participated in the study, the supporters of the “kickstarter” project to develop the StrC; and to the usual cheering crowd: my family (Rita, Sofi, and Martin), my teaching assistants, students, and friends, my Biomimicry Alberta colleagues, and my direct line to nature: our dog Rumba (2007–2019) and our cat Gato. Finally, I thank my dad for always insisting that education makes your life better.

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Glossary

1D ~ One-Dimensional Structure [Structural Colour]: it refers to light only being interfered by the structure in one direction.

2D ~ Two-Dimensional Structure [Structural Colour]: it refers to light being interfered by the structure in two directions.

3D ~ Three-Dimensional Structure [Structural Colour]: it refers to light being interfered by the structure in all three directions.

Academic Prototyping: a way of producing new knowledge about specific ideas through the design of a prototype. The production of the prototype is but one phase in a critical process.

Affordance: resource or support that the environment offers an animal (including humans); the animal in turn must possess the capabilities to perceive and use the resource or support.

Agency: the capacity, condition, or state of acting or of exerting power.

Analogy [biology]: similarity of function and superficial resemblance of structures that have different origins.

Anthropocentric: view that human beings are the most significant entity in the universe. A state of interpreting or regarding the world only in terms of human values and experiences.

Aposematism: animal's use of a visual signal of conspicuous markings or bright colours to warn predators.

Approach [research]: a way of dealing with research questions/problems; a way of doing or thinking about them that implies a methodology.

Arthropod: invertebrate animal of the large phylum *Arthropoda*, such as an insect, spider, or crustacean.

Autopoiesis: from the Greek *poiesis,* meaning making, creation, production. The theory that living systems are "self- organized" mechanisms that maintain their particular form despite material inflow and outflow, through self-regulation and self-reference. Proposed by Chilean scientists Humberto Maturana and Francisco Varela.

Avian: relating to birds.

Axiology: branch of philosophy dealing with ethics, aesthetics, and religion (Guba and Lincoln, 1994).

Biocentered: an ethical point of view that extends inherent value to all living things. It stands in contrast to anthropocentrism.

Bio-domestication: different from biomimicry, bio-domestication is the process of adapting plants and animals to help solve human design problems.

Bio-utilization: similar to bio-domestication, it uses biological beings to solve human problems.

Biomechanics: the study of the mechanical laws relating to the movement or structure of living organisms. Seminal authors on biomechanics are Vogel and Davis (2000), who wrote *Cats' paws and catapults: Mechanical worlds of nature and people.*

Biomimetic: a term for the use of natural models in technology innovation (coined by Otto Schmidt in 1950), and the closest predecessor to biomimicry, frequently used interchangeably.

Biomimicry: "an approach to innovation that seeks sustainable solutions to human challenges by emulating nature's time-tested patterns and strategies" (Biomimicry Institute, 2017), term coined by Janine Benyus in his book *Biomimicry* (1997) strongly inspired by the biophilia hypothesis.

Bionics: an application of biological methods and systems found in nature to the design of engineering systems and modern technology, frequently associated with robotics and biomechanics.

Biophilia: a hypothesis suggesting that humans possess an innate tendency to seek connections with nature and feel affiliated with other forms of life. The term was introduced by E. O. Wilson in his book, *Biophilia* (1984).

Biophotonics: the study of optical processes in biological systems, both those that occur naturally and in bioengineered materials, also seen as an emerging field derived from physics.

BioTRIZ: problem-solving, analysis, and forecasting tool derived from the study of patterns of invention in the global patent literature. It was developed by the Soviet inventor Genrich Altshuller in 1946.

Cross-disciplinary: a general term used to refer to any activity that involves two or more academic disciplines.

Crypsis: the ability of an animal to avoid observation or detection by other animals.

Cymatics: the study of wave phenomena of visible effects, sound and vibration.

Data Analysis: a process of inspecting, cleaning, transforming, and modeling data with the goal of discovering useful information, suggesting conclusions, and supporting decision-making.

Data Mining: an interdisciplinary subfield of computer science. It is the computational process of discovering patterns in large data sets involving methods at the intersection of artificial intelligence, machine learning, statistics, and database systems.

Data Visualization: a general term that describes any effort to help people understand the significance of data by placing it in a visual context.

Deterministic: relating to the philosophical doctrine that all events, including human action, are ultimately determined by causes regarded as external to the will.

Diffraction [physics]: similar to interference, diffraction is a phenomena arising from self-interaction and the superposition of waves of light.

Diffraction Grating: Structural colour mechanism consisting of a surface structure, a nano-scale array of parallel ridges or slits (similar to a corrugated or regularly textured surface) that disperses white light into its constituent angular wavelength/colour components.

Discipline: an established branch of knowledge taught in higher education. It usually involves research and practice in a field of study.

Disciplined Field: a field of study that is evolving into a discipline, also known as an emerging discipline

Ecosystem: a biological community of interacting organisms and their physical environment.

Embodiment: a tangible or visible form of an idea, quality, or feeling.

Emerging Discipline: a new discipline usually evolved from a more general field of study.

Empiricism: a philosophical doctrine that all knowledge is derived from sense experience and practice, usually contrasting with rationalism.

Entropy [physics]: a thermodynamic quantity representing the unavailability of a system's thermal energy for conversion into mechanical work, often interpreted as the degree of disorder or randomness in a system.

Epicultural Process: the learning process of mankind-at-large. Similar to the evolutionary sequence of genetic information, "an epicultural process might partly circumvent the evolutionary sequence of events of which it makes us aware" (Jantsch, 1980).

Epistemology: a set of rules for the appropriate way to generate knowledge, especially to frame methods, validity, and scope, "what counts and does not count as authentic knowledge and also how that knowledge is structured and represented" (Williams, Roberts, & McIntosh, 2012).

Ethnocentrism: a sociology term for the belief in the inherent superiority of one's own ethnic group or culture. A tendency to view alien groups or cultures from the perspective of one's own.

Ethnography: the study and systematic recording of human cultures.

Ethology: the study of animal behavior with an emphasis on the behavioral patterns that occur in natural environments.

Evolutionary Biology: a subfield of biology that studies the evolutionary processes that produced the diversity of life on earth.

Family: A biology term (plural: familiae) for one of the eight major taxonomic ranks; it is classified between order and genus.

Field or Field of Study: a branch of knowledge, usually leading to or containing disciplines.

Generalist: A design term for a person whose knowledge, aptitudes, and skills are applied to a field as a whole or to a variety of different fields (as opposed to a specialist). A generalist designer has a broader view to understand the sources of the problems before moving forward and trying to solve them. Victor Papanek refers to professionals who take these challenges as "reflective practitioners," those designers who are "inclined to engage messy, but crucially important problems" (Papanek, 1985).

Haptic: relating to the sense of touch, in particular relating to the perception and manipulation of objects using the senses of touch and proprioception.

Hermeneutics: the branch of knowledge that deals with interpretation.

Homology [biology]: any characteristic of biological organisms that is derived from a common ancestor.

Hue: a discernible colour that is dependent on its dominant wavelength, and independent of intensity or lightness.

Hylomorphism: a philosophical theory developed by Aristotle, which conceives being (ousia) as a compound of matter and form.

Hyperspectral Imaging: a way to collect and process information (such as reflectance and luminosity values) from across the electromagnetic spectrum (visible colours of the spectrum) using a hyperspectral camera.

Information Design: a subdiscipline of visual communication design, the practice of presenting information in a way that fosters efficient and effective understanding.

Interpretivism: an approach to social science that opposes the positivism of natural science; it holds that not all rationally assertions can be scientifically verified.

Interdisciplinary: refers to two or more academic disciplines or fields of study combined or involved for a common cause.

Interface: a boundary across which two ends communicate; a device, program or layer of information enabling a user to communicate with a computer or artifact, e.g., a computer screen, browser, website, or app.

Interference: A physics term that refers to processes by which one or more waves of light combine with one another in a superposition.

Iridescence: a vivid rainbow-like or metallic colour caused by a differential refraction of light waves (due to structural colour mechanisms) that tends to change as the angle of view changes.

Kingdom: A biology term for the second highest taxonomic rank below domain. Kingdoms are divided into smaller groups called phyla.

Method: A research term for the careful study of a given subject, field, or problem, undertaken to discover facts or principles.

Methodology: the systematic, theoretical analysis of the methods applied to a field of study.

Mixed Methods: A research term for the mixing of qualitative and quantitative data, methods, methodologies, and/or paradigms in a research study or set of related studies. Mixed methods research must be differentiated from multiple methods research.

Mock-up: A design term for a realistic representation of what a product or final design could look like, usually obtained by a refined sketch or preliminary rendering. A mock-up version must be distinguished from a working prototype.

Multidisciplinary: refers to several academic disciplines or professional specializations (usually more than a few) in an approach to a topic or problem.

Multidisciplinary Field: refers to a field of study that involves a number of different disciplines.

Multilayer Reflectors: Structural colour mechanism, consisting of multiple thin films or multilayer systems of comprising pairs of thin films.

Multiple Methods: often confused with mixed methods, it refers to the use of a number of different methods separately. These methods are not necessarily connected or combined, and are meant to solve different aspects of a research problem.

Nanomaterial: materials in which a single unit is sized (in at least one dimension) between 1 and 1,000 nanometres.

Nanoparticles: particles between 1 and 100 nanometers in size. In nanotechnology, a particle is defined as a small object that behaves as a whole unit with respect to its transport and properties.

Nanoscale: relating to microscopic particles of matter, devices, etc., that are measured in nanometers or microns.

Objectivism: philosophical doctrine that holds that all reality is objective and external to the mind and that knowledge is reliably based on observed objects and events. For objectivists, what is right or wrong does not depend on what anyone thinks is right or wrong.

Order: a biology term for one of the eight major taxonomic ranks used in the classification of organisms, e.g., order coleoptera (beetles).

Overspecialization: in disciplines, professional, practices and analogically to nature, overspecialization is seen as the risk of becoming isolated by specializing in one thing only and losing the capacity to adapt to do other things, which in nature leads to stagnation and eventually to extinction. Arthur Koesler, Victor Papanek, and David Orr, among others, use this analogy to describe alternatives to overspecialization, such as generalism.

Paradigm: "a basic set of beliefs that guides action" (Guba, 1990).

Phenomenology: the study of structures of consciousness as experienced from the first-person point of view.

Photonic Crystals: Structural colour mechanism, consisting of crystalline structures (usually three-dimensional) producing gem-like reflectance.

Phyllum: A biology term for one of the eight major taxonomic ranks below kingdom and above class.

Phylogeny: the evolutionary development and history of a species or higher taxonomic grouping of organisms, usually visualized as a branching-out tree.

Positivism: a philosophical system that holds that every rationally justifiable assertion can be scientifically verified.

Post-positivism: shares a basic perspective with positivism, but recognizes that all observation is fallible and prone to error and that all theory is revisable.

Praxis: the process by which a theory, lesson, or skill is enacted, embodied, or realized**.** This concept was introduced by Plato, and continued by Aristotle. Unlike *poiesis,* which requires skills, *praxis* requires virtue.

Precedent-based Design/Precedent-based Research: the process of the selection of relevant concepts from prior case studies in order to apply ideas and conceptual solutions to current case studies.

Probes: a cultural term, cultural probes (or design probes) are a technique used to inspire ideas in a design process.

Prototype: a design term for an early sample, model, or release of a product built to test a concept or process or to act as a thing to be replicated or learned from. Prototypes are often described as "working prototypes" and need to be differentiated from mock-up versions, which are not "working versions."

Qualitative Research: a method of inquiry employed in many different academic disciplines, it is primarily exploratory research. It is used to gain an understanding of underlying reasons, opinions, and motivations. It provides insights into the problem or helps to develop ideas or hypotheses that quantitative research cannot.

Quantitative Research: the systematic empirical investigation of observable phenomena using statistical or mathematical data or pre-existing statistical data manipulated using computational techniques.

Rationalism: in epistemology, rationalism is the view that regards reason as the source and test of knowledge. Rationalists claim that there are significant ways in which our concepts and knowledge are gained independently of sense experience, usually proposed by empiricism.

Reflective: applying a thoughtful, meaningful and deliberative thinking process to a subject.

Reflexive: refers to circular relationships between cause and effect, where researchers are involved in the process as much as participants.

Relativism: the philosophical position that all points of view are equally valid, and all truth is relative to the individual.

Rhizome: Eric Jantsch uses the concept rhizome as a metaphor to describe one of the three ways we may experience evolution in a non-linear, perpendicular process, cutting across the direction of historical space-time to become condensed in the present. Rhizome is a rootlike subterranean stem, commonly horizontal in position, that usually produces roots below and sends up shoots, progressively, from the upper surface.

Rich-Prospect Browser: experimental interface in which the home page displays a visual representation of every item in a given collection, combined with tools for manipulating the display.

Scattering: a physics term that refers to the process by which light waves' propagation is altered by a foreign particle or group of particles.

SEM ~ Scanning Electron Microscopy: a type of electron microscope that produces images of a sample by scanning it with a focused beam of electrons. The electrons interact with atoms in the sample, producing various signals that contain information about the sample's surface topography and composition.

Species: a group of living organisms consisting of similar individuals capable of exchanging genes or interbreeding. The species is the principal natural taxonomic unit, ranking below a genus.

Specimen: an individual animal, plant, piece of a mineral, etc., used as an example of its species or type for scientific study or display.

Stochastic Order: In probability theory and statistics, a stochastic order quantifies the concept of one random variable being "bigger" than another. Stochastic processes are widely used as mathematical models of systems and phenomena that appear to vary in a random manner. They have applications in many disciplines such as biology.

Symmetry: a physics term, the symmetry of a physical system is a physical or mathematical feature of the system (observed or intrinsic) that is preserved or remains unchanged under some transformation.

Synesthesia: a sensation produced in one modality when a stimulus is applied to another modality, as when the hearing of a certain sound induces the visualization of a certain colour.

Systematics: a biology term for the study of the diversification of living forms, both past and present, and the relationships among living things through time. Relationships are visualized as evolutionary trees (phylogenetic trees, phylogenies).

Taxa: a biology term for a group of one or more populations of an organism or organisms seen by taxonomists to form a unit.

Taxonomy: the science or technique of classification, usually visualized as multi-hierarchical tables.

Teleology: a philosophy term for the explanation of phenomena according to the purpose they serve rather than the cause by which they arise.

Text Analysis: the various processes by which text and natural language documents can be modified so that they can be organized and described.

Thermodynamics: the branch of physical science that deals with the relationships between heat and other forms of energy (such as mechanical, electrical, or chemical energy) and, by extension, the relationships between all forms of energy.

Trans-disciplinarity: a research term that is defined as research efforts conducted by investigators from different disciplines working jointly to create new conceptual, theoretical, methodological, and translational innovations that integrate and move beyond discipline-specific approaches to address a common problem.

Tunable: a structural colour term that refers to the colour-changing capabilities of certain species to produce colour by modifying their morphology or physical characteristics at the surface level of their morphology, thereby altering, activating, or deactivating their structural colour mechanisms.

User-centered: a design term for a framework of processes (not restricted to interfaces or technologies, but often associated with them) in which the needs, wants, and limitations of end users of a product, service, or process are given extensive attention at each stage of the design process.

UX (User Experience): an approach to product development that incorporates direct user feedback throughout the development cycle (human-centered design) in order to reduce costs and create products and tools that meet user needs and have a high level of usability (are easy to use).

Wicked Problem: a kind of problem that is difficult or nearly impossible to solve completely, because of incomplete, contradictory, and changing requirements that are often difficult to recognize. Horst Rittel introduced the concept in 1972, suggesting that all design problems are in a sense potential wicked problems, from which ill-formulated solutions can lead to more and higher level problems.

Widget: a computing term for a small application with limited functionality, usually associated with a main interface or home page. A widget's role is that of a transient or auxiliary application.

CHAPTER 1: INTRODUCTION

"All our science, measured against reality, is primitive and childlike–
and yet it is the most precious thing we have." ~ Albert Einstein

This dissertation is situated at the verge of contemporary paradigmatic changes, in the way artifacts and services of design are shaped by new knowledge and new technological advances inspired by the natural world. The research conducted for this dissertation implies discussing, challenging, redefining, and transforming key disciplinary realms as a prospective fusion into emerging disciplines. This fusion mixes different epistemologies under a common purpose: moving from purely anthropocentric and degenerative ways of thinking and doing, to biocentered, regenerative, and ultimately sustainable ways. The disciplinary realms involved in this project—Design, Computing, Material Culture, Human Ecology, Biology, Physics—are, along with other disciplines, being transformed by the challenges of a sustainable future. These transformations require fluid disciplinary exchanges, mutualism and cooperation, and overall, the seeking of spaces, tools, and methods that facilitate these interdisciplinary dialogs.

This dissertation proposes the conception of a tool—StrC, a *rich-prospect browsing probe* for *academic prototyping*—to investigate and test ways to contribute to such transformations, under the theme *structural colour*. In recent years structural colour has turned into a case study for biomimetic design innovation, yet has not been fully explored and not fully applied by human ingenuity. The main goal is to explore a central assumption: the existence of disciplinary gaps that prevent the science of structural colour to be discovered, understood, and adopted by designers to develop biomimetic innovation. This goal also implies finding ways to bridge such gaps by design. The central assumption is complemented by three other inherent assumptions: that there is abundant scientific information on structural colour available, that structural colour implementation has not been fully explored and applied in products and materials yet, and that effective tools like StrC may help to bridge the interdisciplinary gaps and facilitate the implementation of structural colour for biomimetic innovation. The main goal also is motivated by the significance of adopting a biocentered design approach for sustainable practices.

A comprehensive literature review from a multidisciplinary philosophical perspective gives the background and context that informed this research, with an emphasis on the biocentered approach. The methodology pages offer an extensive revision of options to conduct a multidisciplinary research study, under a multidimensional approach that combines multiple methods for the challenge: precedent-based design, academic prototyping, rich-prospect browsing, cultural probes, hermeneutics, and fieldnotes. The full academic prototyping experience of the StrC, the planning, deployment, execution, and administration of the research tool, is described as a central aspect of this dissertation. Equally important are the preparation of the study, collection, administration, and analysis of data obtained through quantitative metrics from the interactions with the tool, and qualitative material from a survey and a series of interviews. The study findings are summarized in a narrative that includes data collected from the study, supported by hermeneutic visualizations to facilitate interpretations and discussions. The conclusions summarize important points and recommendations for future development of tools like the StrC, and reflect on the relevance of the outcomes of this dissertation and the dissertation's continuation as a long-term project. This introductory chapter outlines in detail the six chapters in which this content is organized.

1.1 Scope and Relevance of the Subject: Structural Colour for Biomimetic Design Innovation

To designers, one of the most attractive areas of biomimicry is colour manifested in nature. More specifically, how colour in nature is *differently* manifested from human ingenuity in the way it is produced. Colour in nature has evolved to be frugally produced and effectively used, in addition to meeting—as most natural solutions do—the highest standards of sustainable design; that is, achieving environmentally, socially, and economically balanced outcomes with viable, bearable, and feasible resources. As a result of almost 4 billion years of a “research and development” process, life forms have evolved to achieve amazing “design solutions” (Benyus, 1997). The achievements are even more astonishing when we observe colour. The evolution of eyes affected the evolution of colour from the time of the Cambrian explosion, which was only 550 million years ago, meaning the evolution of colour was eight times shorter than the evolution of life. Life forms produce colour in such ways that our most sophisticated visual technologies seem still rudimentary in comparison. Structural colour is one of the ways nature produces colour without relying on toxic chemistry, pollution, and wasteful processes of fabrication.

The invitation to innovate with structural colour may appear attractive to many designers interested in, for example, the sustainable and biomimetic design of products, materials, communication technologies, and within the printing industry. However, finding, understanding, and implementing the available scientific information to feed the design process pose a major challenge. This is in contrast with the abundant scientific and scholarly published literature on the subject, written by seminal authors such as Richard Prum and Rodolfo Torres (2003, 2004), Andrew Parker (1998), and Peter Vukusic (2004) among many others mentioned in this dissertation, who have worked in the field of biophotonics for decades. It also is in contrast and conflicts with the many prototypes of new materials and technologies that have been developed by different labs around the world, even before the term biomimicry was coined. This critical mass of research is not fully represented in any available comprehensive database (e.g., AskNature.org, PeTal, ITIS.gov, etc.).[2] Collections of cases, as in AskNature.org, are focused on collecting existing cases of implementation organized by function, and not necessarily on collecting information to develop new cases. This approach makes things difficult for researchers, who are denied access to potential cases of structural colour whose functions are not yet completely understood.

Making scientific information available and understandable to designers remains a major challenge. This situation is evidenced in international conferences and symposia on biomimetics and biophotonics. On one side are the seminal scientists, experts on structural colour, with their suggestions that a gap may exist. They are willing to share and see their research transformed into implementation. On the other side are designers dealing with limitations for understanding and translating scientific work into design solutions.[3] A big contrast is suggested when observing the correlation between the growing number of scientific papers on structural colour (on studying and implementing) and the numbers of prototypes and products released to the market in recent years (Smith, Bernett, Hanson, & Garvin, 2015; see Fig. 1.01).

1.2 Study Purpose and Research Questions

These gaps in communication between scientific disciplines and design disciplines may create limitations in accessing and understanding available scientific data useful for biomimetic design projects. Hence, a two-part correlated research question is formulated in this research project: How can a biocentered design approach to colour help bridge gaps between scientific knowledge and biomimetic design practices? How can available scientific information and knowledge on structural colour be better organized and more accessible to bridge such gaps?

[2] See Chapter 4.2 for a summary of current repositories and databases to collect cases of structural colour
[3] Based on researcher's personal conversations with scientists from the "Living Light Conference" biophotonic community between 2016–2018, and naturalists at the University of Alberta between 2015–2019.

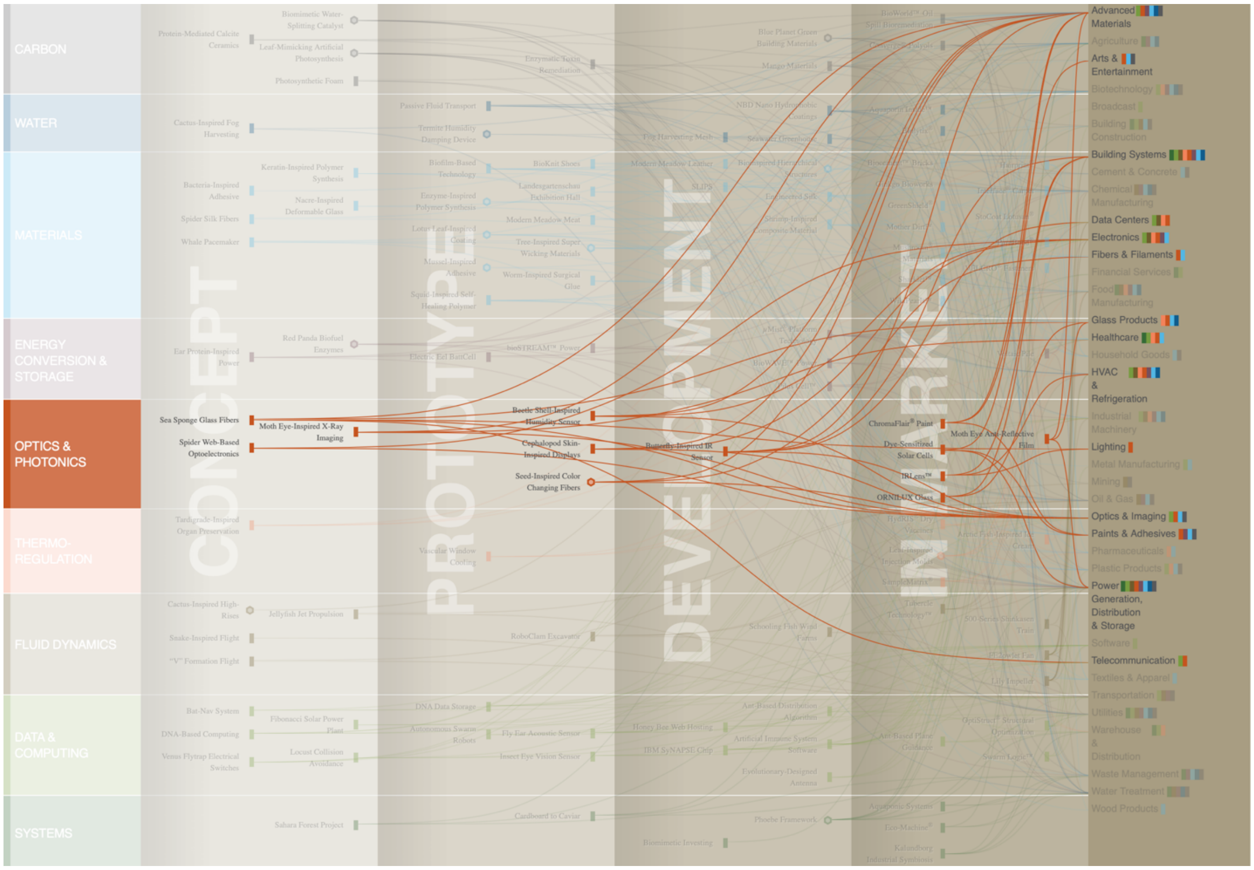

Figure 1.01. Number of cases known of biomimetic optics and photonics cases, branching out from concepts to prototyping (Smith et al., 2015). Only a few of these cases were developed as pilot products to reach the market in the last 10+ years.

Guided by the research question, the main objective of this research project is to investigate ways to facilitate bridging scientific knowledge with potential biomimetic design implementation. The direction of this research is influenced by a design practice-based epistemological background, an interdisciplinary interest, and the emergence of a biocentered design perspective. The literature review in Chapter 2 informs and guides this research reasoning and the methodological decisions made. The nature of the two-part correlated research question also responds to a disruptive mode of inquiring, also known as *problematization* (Sandberg & Alvesson, 2011). This approach contrasts traditional research questions grounded in the *gap-spotting* approach.[4] The research question can be seen as a quasi-*problematization* (Sandberg & Alvesson, 2011)—a moderate version of a problematization question—combined with a track-bound literature-based approach. A problematization or quasi-problematization-based research question enriches this work with significant research theories discussed (i.e., anthropocentrism, biophilia, and biocentrism). Problematization questions are less frequent and more challenging than gap-spotting questions (Sandberg & Alvesson, 2011); however a problematization approach is better suited to the nature of this project.

This research project allowed me to work with experts from both the scientific and biomimetic design communities to explore how visualizing scientific data through the use of a rich-prospect browsing[5] environment (Ruecker, 2003; Ruecker, Radzikowska, & Sinclair, 2011) may bridge knowledge about structural colour in nature, connecting scientific research to design innovation. The rich-prospect browsing environment was implemented using the concept of "academic prototyping" (Ruecker, Adelaar, Brown, & Dobson, 2014), an ethnographic design method that provides opportunities to produce new knowledge through the design of a prototype. The prototype developed was a digital interface customized for this research study. Such an interface, which can be defined as a rich-prospect browser with academic prototyping characteristics, is called Rich-Prospect Taxonomy on Structural Colour or "StrC." The inclusion of the term "taxonomy" reflects the experimental nature of this tool, since any taxonomic

[4] Gap-spotting questions are those that try to identify gaps in existing literature, and tend to reinforce rather than challenge influential theories (Sandberg & Alvesson, 2011).
[5] A Rich-Prospect Browser is an experimental interface, in which the home page displays a visual representation of every item in a given collection, combined with tools for manipulating the display. This concept if fully developed in chapter 3.4.

ordering is also experimental, rather than a descriptive science (de Hoog, 1981). The way the data is organized in a taxonomic manner follows a biological science criterion.

1.3 Significance of the Study

Connecting scientists with designers may create interesting synergies and opportunities for biomimetic implementation. Making scientific knowledge on structural colour available and access to such "designers-friendly" information may accelerate design innovation and allow the discovery of new areas for biomimetic exploration. Learning from nature how colour can be produced sustainably is a prospect that has opened the minds of scientists and designers alike to a new foundational philosophical level. The challenge is not a simple one, but the momentum created by the emerging disciplinary field of biomimicry helps to achieve this project goal: to facilitate connections (e.g., scientists-designers, scientists-scientists, and designers-designers) for biomimetic innovation. Facilitation or cooperation is also a lesson to learn from nature. Facilitation is a beneficial interaction between species; that is, it stands in direct contrast to the mutually negative effect of competition (Baumeister, 2019). Scientists and designers do not share methodologies; the ways of knowing and sharing is quite different from one realm to the other. However, the commonalities between science and design override the differences. The inquisitive nature, the problem-identifying and problem-solving capacities, and the high incidence that new findings and products from both realms have on our civilization make the task of gathering both domains around the same table not only feasible but also highly relevant. Scientists and designers alike are entangled in the ethos of "figuring things out" (Fig. 1.02).

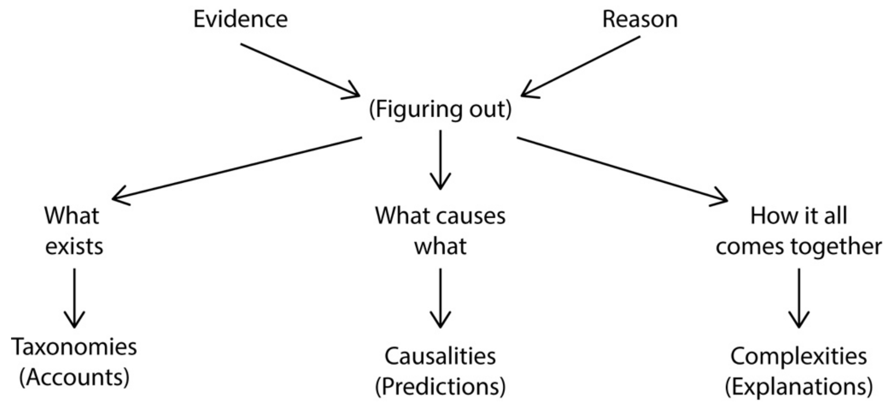

Figure 1.02. The dynamic of the scientific ethos. From the lecture *Nature, Science, and Science Communication* given by Dr. John Acorn[6] at the R.E. Peters Biology Conference, March 8, 2019, University of Alberta.

The purpose of the study is to find and test ways of bridging these multidisciplinary spaces. The study implies an ongoing discovery process and an open-end academic prototyping experience. The outcomes of interactions between scientists with designers, scientists with peer scientists, and designers with peer designers offer new possibilities to discuss unexplored terrain in structural colour understanding and implementation. The findings show important angles from which to address the research questions initially proposed, as well as to present new areas for discussion and new questions to investigate (fully developed in Chapter 5). Below is a list of the areas of continuing discussion that connote the questions and responses of the study:

- The purpose of colour in life forms
- The natural strategies to create and read colour
- The evolutionary aspects of developing pigmentation versus structural coloration mechanisms
- The diversity of species with different external stimuli and from entirely different ecosystems, converging with similar structural colour mechanisms
- The different structural colour results observed within the same species
- How can all these evolutionary features of structural colour be explained in comparative problem-solving terms

[6] Dr. Acorn is an entomologist and naturalist, lecturer at the University of Alberta, author of many books on Alberta's biodiversity, and host of the famous television series *Acorn, the Nature Nut*.

1.4 The Dissertation Roadmap

The overarching process of this doctoral project can be described as a chronological sequence of events, from initial steps to the instances of definition, elaboration, final deliverables, and publishing. This process involved five phases, described below.

Phase 1 consisted of preparing the terrain for the scholarship, by completing the coursework in Human Ecology, Material Culture studies, and elective subjects. These courses made it possible to do several things: build the literature review, help to consolidate a critical standpoint (a reflective approach to philosophical implications of the area of interest), and make methodological choices to conduct research. Phase 1 involved exploring and examining a biocentered approach (Benyus, 1997; Helfman Cohen & Reich, 2017) for sustainable and restorative design (Montana-Hoyos & Fiorentino, 2015; Wahl, 2016) based on the instinctive bonds between humans and nature (i.e., *biophilia*; Kellert, Heerwagen, & Mador, 2008; Wilson, 1984), and enriched by material culture (Bennett, 2010; Ingold, 2007; Knappett, 2007; Latour, 1999; Moran, 2010; Sacks, 2005) and human ecological perspectives (McIntosh, 2012; Steiner, 1995; Strauss, 1990). This made it possible to focus on finding and collecting evidence and empirical case studies of the implementation of bio-inspired designs on the subject of structural colour. Extensive literature searches (Bernard, 1995) showed that there is evidence of early stages of bio-inspired design in relation to the study of colours in nature. This phase also extended the understanding of colour in nature: namely how it is generated, manipulated and used by life forms; the physics of colour; and the evolutionary aspects of colour development. At the end of this phase, two presentations were delivered: “[A] Biomimetic Approach to Colour” at the Doctoral Colloquium, IASDR 2015 conference (November 2, 2015, Brisbane, Australia) and “Biomimetics of Colour” as a visiting lecturer at the University of Canberra (November 5, 2015).

Building on Phase 1, Phase 2 included the design of a Rich-Prospect Taxonomy on Structural Colour (the StrC) in the form of a self-administered database, a digital interface, and data visualization components. The strategy proposed contains the rigour of taxonomic information (de Hoog, 1981) combined with the flexibility, interactivity, and visual effectiveness of "rich-prospect browsing" (Ruecker et al., 2011). The goal was to develop and test this tool among designers and scientists as part of the study, to address the research questions formulated and inform this doctoral dissertation. To work on this phase, two independent studies (HECOL 501 and HECOL 651) were set to fulfill the coursework requirements and help develop the research tools. At the end of this phase, two poster presentations were delivered: "A Dynamic Taxonomy on Structural Colour" at the 11th International Conference on Design Principles & Practices (March 2–4, 2017, Institute Without Boundaries, Toronto), and "DTSC: A Case of Academic Prototyping" at the ALES Graduate Research Symposium (March 17, 2017, University of Alberta).

Phase 3 focused on preparation for comprehensive exams and candidacy exams. As a result, four papers were written—"Methodological Thinking: Strategic Decisions on Choosing Research Methods"; "Sustainable Design Informed by Nature: Biomimetic Approach to Structural Colour"; "The Nature of Material Culture"; and "Philosophical Implications from Biocentered Design and Human Ecology Perspectives"—to demonstrate knowledge on the key components and subjects involved in this doctoral scholarship, the methodology, the substantive area of study, the material culture realms, and the human ecology ways of knowing.

Phase 4 focused on conducting the StrC comprehensive study (fully developed in Chapter 4). This phase also consolidated the working prototype of the StrC interface for future development and to extend the data access to external repositories. During this phase, two presentations were delivered: a poster on "Sustainable Colours" to the 15th International Conference on Environmental, Cultural, Economic & Social Sustainability (January 18, 2019, University of British Columbia), and an update on the StrC study at the ALES Graduate Research Symposium (March 13, 2019, University of Alberta).

Phase 5 focused on data analysis and writing the conclusions and final chapters of this dissertation. During this phase the results of the StrC study were presented for the first time to a community of design innovators and scientists in the area of nature-inspired design, at the American Institute of Science's (AIS) Nature Inspired Surface Engineering (NISE) Conference (June 14, 2019, Stevens Institute of Technology, New Jersey, USA). The dissemination of this project will continue beyond this dissertation, at the Living Light Biophotonics Conference (Australia in 2020), and other future symposia on the subjects of biophotonics and biomimetic design. More outcomes of this research project beyond this doctoral dissertation involve publishing results in peer-reviewed journal articles. Future steps of the project will focus on making the system accessible for public use.

1.5 Outline

This dissertation is organized into six main chapters, complemented by a Glossary, References, and an appendices. Chapter 1 is this introduction. Chapter 2 consists of a comprehensive literature review that constitutes a building block that provides an epistemological context, discusses important theories and the works accomplished by other researchers, and sets the framework of this doctoral investigation. The search for literature relevant to the areas of study started during the coursework of this doctoral scholarship, and continued during the writing of four papers required for the pre-candidacy comprehensive exam. In addition to this scholarship, original authors across disciplines (from design, environmentalism, education, economics, and science) were influential as they brought to the research 10+ years of experience investigating and teaching the subject of sustainability in the design curriculum at the University of Alberta. The literature review describes and summarizes the elements from theoretical perspectives that inform and help determine the nature of this research. The chapter concludes with reflections on the pieces of literature that offer the most solid and credible arguments, and make the utmost contribution to knowledge in the area of research of structural colour and biocentered design.

Chapter 3 focuses on the methodological approach and the multiple methods that were applied to this research program. The chapter is influenced by the discussion on anthropocentrism and biocentrism introduced in the literature review chapter. Strategic decisions made about choosing effective research methods demanded a recurrent reference to both anthropocentrism and biocentered thinking. The chapter reviews relevant approaches, ways, and methods used in different epistemologies, with the intention to integrate and emphasize synergies between the diverse perspectives involved in this research. The chapter introduces a multidimensional approach that includes a design generalist approach, a human ecology and material culture (i.e., more holistic and integrative) approach, and a biomimicry (i.e., scientific-design-oriented) approach. It also explains in detail how the methods chosen worked together to address the different stages of the study: collecting, managing, and analyzing data. It also describes the phases of the research, details of the targeted participants for the study, the procedure for data collection, types of data, data analysis used, and anticipated possible limitations. It defines as binomial the two main concepts used in the research: academic prototyping (Brown et al., 2014; Ruecker et al., 2014) and rich-prospect browsing (Ruecker, 2003; Ruecker et al., 2011).

Chapter 4 describes the study, explaining how the prototyping stage was developed according to the methods chosen, and how the study was designed and executed. It also gives a framework for the analysis of outcomes and findings developed in Chapter 5. Chapter 4 describes the design stages, logistics, and implementation of the StrC as an academic prototyping rich-prospect browsing interface, for the purpose of the study guided by the research question—to find ways to bridge scientific knowledge and potential biomimetic design applications. The first section of the chapter gives a background on taxonomies, phylogenies, and tree thinking (Baum & Smith, 2013) as guiding concepts to facilitate scientific information on structural colour. The second section reviews precedent cases of taxonomic databases and repositories, conceptually or functionally related to the StrC. In the third and fourth sections of the chapter, initial scientific questions are identified as a consequence of the academic prototyping process, and the initial assumptions regarding the research question. The fifth section of the chapter describes the entire process of designing and developing the StrC interface, illustrated with diagrams of the project, sketches of the design, and mockup versions of the interface. This section describes contributions from different epistemologies and areas of expertise (e.g., entomology, scientific photography, electromicroscopy, and physics-optics), as well as the programming stages of the initial prototype and database, including development and deployment. The last section of this chapter is dedicated to the planning, execution, data collection, data analysis, and data classification of the study. It describes how the different parts of the study were organized; how the prototype was used in the study; and the logistics, materials, and preparation needed to run the study.

Chapter 5 focuses on the findings. It presents, describes, and analyzes the results, and offers different interpretations that prepare the terrain for further conclusions. It helps to identify and understand the study's limitations, the methods used, and the overall limitations of the subject matters. In addition, it offers initial reflections that anticipates the benefits and opportunities of further development of the StrC project. The chapter is first dedicated to summarizing in detail the results of applying the methods, described in Chapter 3, that were used to collect and analyze the data. The chapter then presents the method's levels of success; identifies milestones, turning points, and pros and cons; and establishes trends and illustrates them with diagrams and data visualizations. It also reflects on negative and positive outcomes from the study. These outcomes demonstrate in some cases the veracity of initial claims, assumptions, and propositions—such as the effectiveness of a tool like the StrC to bridge the disciplinary gap implicit in the research question. Results also revealed new angles to the problem and new questions to ask, as well as contrasted some initial pre-study assumptions. This analysis helped to identify and clarify limitations of the overall design study, the methods used, and the epistemological challenges of the subjects (structural colour, biomimetic design, and a biocentered approach).

Chapter 6, the last chapter, presents the conclusions. It reframes the research question and subsequent questions in light of the findings. It also evaluates limitations, opportunities, and new questions that arose, and summarizes recommendations for future research and considers possible ramifications of such research. It also offers conclusions on the overall doctoral project experience, including a retrospective analysis, the current stage and prospect of the research interests involved in this scholarship, as well as the reasons and purpose for the continuation of this project beyond this doctoral dissertation. The final remarks of this chapter synthesize the outcomes of the overall research experience.

1.6 Preamble

The reader of this dissertation may find it challenging and perhaps provoking from a disciplinary standpoint, philosophically, epistemologically or methodologically, and hopefully also exciting. As the author of this dissertation, I am familiar with that experience; the boundaries of our disciplinary comfort zones get blurry when we face any sort of paradigmatic shifting (e.g., between anthropocentric and biocentered thinking) as it is proposed in this work. Besides the natural complexity of the subject matters presented, the challenge as well as the joy of this research dwells in the diversity of the proposition: exploring disciplinary realms different from each other (at least in some aspects), discovering unnoticed connections or new opportunities to connect, and sparking innovation out of a disciplinary mingling experiment. The realms of design, human ecology, and biomimicry teach us to perceive this process of exploring, discovering, and innovating as part of a reflective practice. This action-reflection process of thinking while experimenting, and experimenting while thinking, also describes a biocentered-thinking attitude towards things that seem unconnected. According to G.K. Chesterton,[7] thinking means connecting things, and stopping if they do not connect. From an evolutionary and biocentered standpoint, this concept is incomplete and can be expanded; stopping if things do not connect is good advice to allow reflection, as long as we "keep going," connecting things after or during the process. In this direction, this dissertation proposes tools and ways for research to be a continuum process and not only a means to achieve things.

Researchers in biomimetic design and the science of structural colour, as well as from other disciplines interested in biocentered thinking, biomimetic sustainable innovation, and interdisciplinary research tools, may find opportunities to enrich their own research in the epistemological, methodological, and empiric work done in this dissertation. An asset of this dissertation is the continuation, directly or indirectly, of the StrC as a tool for interdisciplinary research and as a space to connect scientific knowledge to biomimetic design innovation. The following chapters serve to foster such collaborative purposes.

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[7] Writer and philosopher G.K. Chesterton (1874–1936) was an adherent to some anti-evolutionist ideas that nowadays could be considered controversial to scientists.

CHAPTER 2: LITERATURE REVIEW

This review describes and summarizes the elements from theoretical perspectives that inform and help determine the nature of this research. It is organized from the general to the specific, funnelling down to the research problem. This sequencing of ideas serves as an analytical framework to understand how background, philosophical perspectives, and areas of study connect in this research project. Thus, this review is structured in three sections that define the scholarship: (a) epistemological foundations (design, material culture, and human ecology); (b) philosophical foundations (sustainability, anthropocentrism, biocentrism, and biocentered design); and (c) area of interest (structural colour).

The first section introduces three epistemological domains that set the foundations of this project: design studies, material culture, and human ecology. The second section situates the idea of biocentrism as a means to achieve sustainable ways of design. It proposes a relevant discussion for designers looking for sustainable innovation through the implementation of a biomimetic methodology. The area of focus of the StrC, structural colour, is described in the third section. This section reviews the different traditional colour theories and propositions from philosophers and pioneer scientists, as a precedent to the current knowledge on the phenomenon of structural colour from physics. The last section offers conclusions that will help clarify the direction of this research project and scholarship, based on encounters with and synergies of the scientific ways of knowing and the design ways towards innovation.

2.1 Epistemological Foundations: Design, Material Culture, and Human Ecology

This dissertation is the result of a scholarship that has been shaped by three epistemological domains: design studies, material culture, and human ecology. The foundations of this project are set at the crossroads of these domains.

2.1.1 Design Studies Domain

2.1.1.1 The Nature of Design

In this domain the role of design is addressed in the context of the current anthropocentric paradigm that is fully described in Section 2.2. Design can be seen as a problem-solving and innovative interdisciplinary field, but also as part of a problematic disciplinary present. Contemporary design theory and practice have been limited by the design and industry status quo that gives design a utilitarian role that prioritizes the *doing* over the *thinking*, the superficial over the intrinsic, and intervention over planning (Maldonado, 1972). The limitations of an anthropocentric approach to design, and its practical consequences, outweigh the possibilities of improving the quality of human life while compromising all life existence including that of humans (Buchanan, 1992; Fry, 2005).

2.1.1.2 Design Praxis and Wicked Problems

The kind of problems design has to solve can be considered *wicked problems* (Rittel & Webber, 1973), those problems that lead to ill-formulated solutions and to more higher level problems (Buchanan, 1992). The concept of wicked problems was introduced by Horst Rittel in the 1960s. Rittel suggested that all design problems are in a sense potential wicked problems, from which ill-formulated solutions can lead to more and higher level problems (Buchanan, 1992; Rittel & Webber, 1973). A wicked problem is a kind of problem that is difficult or nearly impossible to solve completely because of incomplete, contradictory, and changing requirements that are often difficult to recognize (Buchanan, 1992). A wicked problem is a systemic problem; it is strong, context-sensitive, or path-dependent (Farrell & Hooker, 2013), which aligns with the way natural evolutionary systems unfold. This description can be easily associated with the kind of problems that anthropocentrism implies and that has led to essential dichotomies. The detachment of humans from nature is one of these dichotomies.

The propositional standpoint that dominates this research project supports the idea that designers are critical thinkers, and should be educated also as problem identifiers, as generalists, and as reflective practitioners (Crouch & Pierce, 2012; Papanek, 1984; Schön, 1983; Strauss, 1990; Strickfaden, Stafiniak, & Terzin, 2015) conscious of design as a field highly contextualized in a wicked problem environment. The arguments for this philosophical standpoint go back to the time of Aristotle. The Greek philosopher proposed a useful concept to define design's practical intellect as *techné* or "knowing by making" (Strickfaden & Devlieger, 2011; Wang, 2013). Thus, a deeper understanding of an overarching design epistemology should differentiate designers as *makers* rather than *doers.* Why is this differentiation important? When design disciplines are limited to play only an anthropocentric role—designers as *doers*—the consequence is a world created by design that is deeply unsustainable; designers as industrial actors "torture" nature as a resource (Capra, 1982), depleting materials for design production, planned obsolescence, and consumerism. When design disciplines align with an intellectual *praxis,* following Aristotle's reasoning, designers become *makers,* capable of enacting, elevating and realizing their role of contributing to the society in a less anthropocentric way. This reflexive understanding of design *making* prepares designers to better deal with the complexity of the wicked problems created in the Anthropocene that led to unsustainability.

2.1.2 Material Culture Domain

2.1.2.1 Materials, Materiality, Culture, and the Coupling of Material/Culture

Material culture connects to design in an intrinsic way. In fact, design disciplines can be seen as basically material culture studies (Miller, 2008). Material culture is the study of consumption, mediation, and production (of artifacts, objects, and the built environment); design implies a similar approach to do research, with an emphasis on production and implementation (design processes, design methods, design thinking, and system thinking). In addition, consumption has been of great interest in design studies for half a century (since the late 1960s), where, for example, colour theory was studied from an audience perception point of view, as well as studied in terms of the psychological and behavioural dimensions of colour (Gertsner, 1986).

For designers, an interest in this material culture-design synergetic relation is strategic. Working with material culture methodologies can make an important contribution to the transition from anthropocentric design to biocentered design. To consolidate such synergetic relationships between design studies and material culture, it is crucial to reflect on the arguments that define materials, materiality, culture and material-culture suitable for a biomimetic design perspective.

2.1.2.2 Argumentation I: The Nature of Material

Jules Prown (1982) defined material culture8 as "the study through artifacts of the beliefs—values, ideas, attitudes, and assumptions—of a particular community or society at a given time" (p. 1). Prown's view implies that a given environment, such as a particular community at a given time, could affect the interpretation of the artifacts, which means that material culture considers artifacts as context-dependent (Hodder, 1994). This interpretation of material artifacts and their contexts creates at least some questioning when it is examined from a biocentered disciplinary angle: Can material culture be effective by being centered only on

[8] Prown (1982) also suggests that material culture is "a means rather than an end, and a discipline rather than a field" (p. 1). Other voices do not refer to material culture as a discipline but as a field of study (e.g., Bennett, 2004, 2009) and others as a subdiscipline under the realms of anthropology and/or sociology (e.g., Miller, 2008). For the purpose of consistency, this document will refer to material culture as a disciplinary field.

studying human species and human-made artifacts? Can non-human-made materials, cultures, artifacts, and contexts be removed from studying material culture?

The meaning of materials and materiality, and their relationship to human culture have been long discussed in material culture realms. Some voices are in favour of a clear distinction between the two (i.e., material as a tangible concept and materiality as a blurry one; Ingold, 2007), and some are in favour of a more holistic view, which sees material and materiality connected as an expression of intangible and subjective values found in human culture (Knappett, 2007; Tilley, 2007). From a material-semiotic and predominantly constructivist angle, Bruno Latour (2014) differentiates matter from materiality in terms of what we can observe from their relation to the past, present, and future:

> Matter is produced by letting time flow from the past to the present via a strange definition of causality; materiality is produced by letting time flow from the future to the present, with a realistic definition of the many occasions through which agencies are being discovered. (p. 14)

These assertions anticipate the relativeness of the concepts when timescales are also considered in understanding matter (proposed in the following pages). In particular, they anticipate the way in which the concept of material varies when moving from an anthropocentric to a biocentered perspective.

In the book *Thinking Through Material Culture: An Interdisciplinary Perspective*, Carl Knappett (2005) describes humans as “biological organisms” and “animated entities,” and he suggests, coincidentally with other seminal voices from material culture, that humans possess “agency” (Latour, 2005, 2014) and “personhood” (Tilley, 2005). Here is an opportunity to use a biocentered mindset to analyze the implications of such a proposed framework. Knappett discusses the perception of the human subject and the material object as if they belong to two separated worlds: the animated and the inanimate. He describes this differentiation assuming that separating living forms from their immediate environment as two categories is the most common approach from a western (anthropocentric) philosophy. However, Knappett gradually takes a different pathway following a more holistic and Aristotelian view, in which the boundaries between animacy and inanimacy get blurry. Aristotle believed that matter and form were very much interdependent and neither could exist without the other. Following this reasoning, Knappett (2005) suggests a sort of mutualism in the way a combination of animated and inanimate can lead to "hybrid super-organisms." This idea of hybridization is also suggested in the interpretation of earth as a superorganism, namely *Gaia* (Lovelock, 1987). Bruno Latour (2014), in addressing the Anthropocene epoch, sees Gaia as an *actor* sharing "our common *geostory*" in a "new form of agency" (p. 3). Interestingly, this idea aligns with nature-centered minds such as James Lovelock and Adrian Bejan, and with other contemporary material culture minds such as Jane Bennett and Daniel Miller.

Lovelock (1987) introduced the hypothesis of Gaia (meaning the earth), sustaining that our planet supports life through an interwoven net of ecosystems and natural forces, turned also into a living form or super-organism. Bejan (2012) elaborated a strong argument for the *Constructal Laws* based on the laws of thermodynamics, the capacity of natural systems to self-organize in response to natural entropy, and the similitude of patterns observed either in animate and inanimate elements. These theories coincide with the work of Maturana and Varela on the theory of *Autopoiesis*, which posits that living systems are "self-organized" (Varela et al., 1974; Jantsch, 1980). Bejan and Zane (2012) argue that these self-organized patterns respond to the way elements and energy "flow" through nature.

Coincidentally, but from a material culture angle, Jane Bennett (2010) connects materiality and materials flow to the concept of natural self-organization, as she refers to “assemblage”: a sort of entanglement phenomenon not governed by a central force but rather by emergent properties of the parts that may organize the whole. Bennett (2004) describes materiality as a “non-Newtonian [non-mechanistic] picture of nature as matter-flow” (p. 349); she calls this phenomenon “thing-power materialism,” a sort of natural agency of things for assemblage: “Thing-power materialism figures materiality as a protean flow of matter-energy and figures the thing as a relatively composed form of that flow” (p. 349). Based on Deleuze’s[9] and Guattari’s[10] interpretation of matter-flows phenomena (Deleuze & Guattari, 1987), and on Maturana’s and Varela’s theory of Autopoiesis (Varela, Maturana, & Uribe, 1974), Bennett (2004) sees an affinity between thing-power materialism and ecological thinking:

> both [thing-power materialism and ecological thinking] advocate the cultivation of an enhanced sense of the extent to which all things are spun together in a dense web, and both warn of the self-destructive character of human actions that are reckless with regard to the other nodes of the web. (p. 354)

Bennett (2004) goes even further in these reflections by analyzing the work of DeLanda (2006) and Vernadsky,[11] who refuse any sharp distinction between the animate and inanimate, life and matter, and resolve these dichotomies by referring to “living matter” (p. 353), a concept that connects to Lovelock’s idea of *Gaia* (Lovelock, 1987) and to the way Latour refers to the earth as an *actor* (Latour, 2014).

The interpretation of materials-materiality and culture varies when the concepts are seen from the two different perspectives implicit in this discussion (anthropocentrism and biocentrism, see Section 2.2 for elaboration). Daniel Miller suggests that, before embarking on

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[9] Gilles Deleuze (1925–1995) was a French philosopher who wrote on philosophy, literature, film, and fine art. His most popular works were the two volumes of *Capitalism and Schizophrenia*: *Anti-Oedipus* (1972) and *A Thousand Plateaus* (1980), both co-written with psychoanalyst Pierre-Félix Guattari, in which they introduced the philosophical concept of Rhizome, what Deleuze called an “image of thought,” based on the botanical rhizome.
[10] Pierre-Félix Guattari (1930–1992) was a French philosopher, semiologist, and activist, and is best known for his intellectual collaborations with Gilles Deleuze.
[11] Vladimir Ivanovich Vernadsky (1863–1945) was the scientist who developed the concept of the biosphere and who is now generally acknowledged as the originator of a new paradigm of life studies.

any definition of material culture, it is vital to consider addressing the meaning of materiality, which can be described from different angles and epistemologies. For an anthropocentric or a biocentered analysis, the negative connotations of materiality provide relevant information to contrast shifting paradigms. In this sense, Miller (2008) observes the cultural, political, and environmental implications underlying materiality, which are particularly shaped by global capitalism, and sees “a continued critique to mass consumer culture as a loss of humanity under a deluge of materiality” (p. 273). Miller finds a consistent ideological fear and opposition to material culture, which he attributes to the association of materiality to materialism.[12] Latour (2014) links this pitfall of materiality to the dichotomy between animate entities with agency versus inanimate things with no agency. This dichotomy creates “a division between the realm of necessity and the realm of liberty that has made politics impossible, opening it very early on to its absorption by The Economy” (Latour, 2014, p. 15). According to Latour, this dichotomy has led to a political polarization around the concept of materiality where “either the margins of actions have no consequence in the material world, or there is no freedom left in the material world for engaging with it in any politically recognizable fashion” (Latour, 2014, p. 15). An anthropocentric bias towards materiality can yet be noticed in Latour’s and Miller’s criticism. This bias limits the discussion on materials, materiality, and culture to the realms of politics and ideologies, and keeps the discussion from being considered part of a paradigmatic shift towards biocentrism.

While the connotations of materiality can lead to an anthropocentrically biased and at times blurry terrain (Ingold, 2007) and a highly problematic narrative act of speculating about

[12] Materialism can be seen as devotion to material wealth, tangible and valuable objects, often associated with consumerism and capitalism.

the future (Latour, 2014), materials may offer more concrete parameters to serve a material culture methodology. Materials imply causality from analyzing the past (Latour, 2014), independent of materiality prejudices and subjectivities, and can facilitate contrasting a biocentered approach from an anthropocentric approach.

From an anthropocentric standpoint—a position that places humans at the center of relevance*,* materials are or can be an expression of human culture. From a nature-centered or biocentered standpoint—a position that places nature and life at the center of relevance and humans as a non-exclusive part of it*,* while the observer is still a human being (us) and therefore the understanding is still inevitably anthropocentric (Moran, 2010), a more holistic, biocentered lens[13] gives the observer a broader angle from which to question the anthropocentric assumptions. Therefore, the term material can be seen as an anthropocentric construction, a convention to understand and communicate what human beings (we) experience and perceive (solid, fluid, and tangible things), while in reality and according to the new scientific domains of physics (i.e., quantum mechanics, physics topology, and new notions of matter, space and time), all things that look and feel material to humans (and to most living creatures) are in fact filled with emptiness if you consider, for instance, scaling down materials to the subatomic level (Capra, 1996, 2010). This is also noticed from a thing-power materialistic perspective which considers matter-energy as a dynamic flow (Bennett, 2004). This relativeness of matter can affect how animate and inanimate things are perceived to the material culture observer as interacting and self-organizing; according to Bennett (2004), particular modes of matter-energy

[13] Examples of holistic lenses include an aboriginal lens, which helps to develop skills physically, mentally, emotionally, and spiritually; and a systems thinking lens, which provides a holistic sense of the complexity and interrelations between the parts. A holistic lens is also used to interpret deliberative technology (a methodology for ethnographic research).

reside “in a world where the line between inert matter and vital energy, between animate and inanimate, is permeable, and where all things, to some degree or another, live on both sides” (p. 352). The idea of relativity of scale and measure is implicit in Bennett’s reflections and illustrated through Deleuze’s and Guattari’s examples: “a fiber stretches from a human or animal to molecules, from molecules to particles, and so on to the imperceptible” (Bennett, 2004, p. 365).

The term *material* then can turn into a fuzzy concept, in the same way that, for example, material borders are unclear when the observer considers the whole scale-range of the physical world. Benoit Mandelbrot (1967) introduced this point when, in the title of a groundbreaking article about the Fractal Theory, he asks, “How Long is the Coast of Britain?”[14] In his argument, he proposed that it is meaningless to talk about the length of a coastline (or any material border); Mandelbrot demonstrates through a mathematical model that the measured length of any physical (i.e., material) object increases without limit as the measurement scale decreases towards zero; in other words, a coastline or any material border can be infinite if all the irregularities and details are measured with extreme accuracy, which makes the very concept of measuring relative.[15] Thus, our intuition alone may not be adequate to the task; materials can actually turn immaterial or less tangible, depending on the scale applied by the observer. Materials, same as coastlines—and rhetorically as culture or nature—are human conventions to make sense of things we experience anthropocentrically.

[14] Benoit Mandelbrot introduced the “Mandelbrot Set” in 1967 which explains mathematically the concept of fractals, initially published in his book *Fractals: Form, Chance and Dimension* (1975) and later in *The Fractal Geometry of Nature* (1982). Since then the Fractal Theory and formulation have questioned assumptions on human ways of measuring reality and materiality. Fractals have also revolutionized the industry of modern computer graphics, mimicking nature.

[15] For instance, if we measure a coastline with a ball of yarn, say from north to south, extending the yarn in a straight line it may measure a number of meters or kilometers. If we use the same yarn following all the irregularities of the coastline (rocky borders, sand, etc.) the yarn would have to be much longer.

2.1.2.3 Argumentation II: The Nature of Culture

Material is not the only troubling concept that changes interpretation according to the lenses used; culture is a challenging concept, too. From a structuralist[16] standpoint, Pierre Bourdieu (1970) considers nature as opposed to culture (p.153). In "Agency at the Time of the Anthropocene," Bruno Latour suggests that science aligns to some extent to this distinction (Latour, 2014), and he refers to the work of geologist Peter Westbroek in *Life as a Geological Force: Dynamics of the Earth* (Westbroek, 1991). Westbroek (1991) asserts that "We are cultural, not natural, beings" (p. 220). This interpretation of both nature and culture, however, differs from the views of other intellectuals within material culture realms, positioned from a posthumanist[17] standpoint. These intellectuals include Tim Ingold (2010) and Joe Moran (2010), and from theorists from other epistemologies like J.J. Gibson (1977) from psychology, E.O. Wilson (1984) from biology, or Fritjof Capra (1982, 1996, 2010) from physics. Their posthumanist standpoint is that nature and culture are not only *not* opposed but intrinsically entangled. Dieter Steiner (1995) offers a midpoint in this division of views, while his approach still aligns with Bourdieu's binary anthropocentric approach (nature vs culture, man-made versus natural), he also proposes a more holistic and inclusive approach. Steiner contends that biology and culture have evolved together in a "recurrent pattern" during human history, and he criticizes the foundation of our current monoculture society (i.e., a characteristic of anthropocentrism) as the cause of an "evolutionary inversion" that depicts a current crisis in humanity (Steiner, 1995,

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[16] In sociology, anthropology, and linguistics, structuralism is the methodology that elements of human culture must be understood by way of their relationship to a larger, overarching system or structure. Intellectuals such as Bourdieu, Levi Strauss, and Althusser were concerned with structuralism and semiotics. Increasingly through semiotics, other influential intellectuals such as Baudrillard, Foucault, and Barthes developed a new system, post-structuralism, in the late 20th century, as an alternative standpoint to pure structuralism (Miller, 2004).
[17] Posthumanism aims to develop, in ways that are safe and ethical, technological means that will enable the exploration of the posthuman realm of possible modes of being. It is also a critique of humanism, emphasizing a change in our understanding of the self and its relations to the natural world, society, and human artifacts.

p. 42). *Deep Ecology*[18] regards human life as just one of many equal components of a global ecosystem (Kellert et al., 2008). Radical ecologists aligned with this view, and also argue that one of the roots of the environmental crisis is anthropocentrism and its view that humans alone are the origins and measure of all value (Dias, 2002). Radical Human Ecology proposes a cosmological interpretation of the role that humans play on this planet, as stewards of the "household" in which we live (McIntosh, 2012), to protect it and not to exploit it as a resource for our exclusive needs. All these concepts—Radical Human Ecology, Deep Ecology, and Radical Ecology—lie philosophically in what can be now considered posthumanist ideas (Bennett, 2010).

Paradoxically (and anthropocentrically), focusing only on human needs means running the risk of losing a sense of humanity. In the design methodology realms, for instance, *human-centered* and *user-centered* approaches lack depth when the human scale needs to meet nature's scale. Focusing only on human perception and human needs can lead to a biased, distorted[19] interpretation of reality[20] and to a limited interpretation of the problems observed. Jane Bennett (2010) asserts that human-centered agency is characterized by "a certain looseness and slipperiness often unnoticed" (p. 28). In this sense, the unintended consequences of human-

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[18] In 1973, Norwegian philosopher Arne Naess introduced the phrase "deep ecology" to environmental literature. After environmentalism emerged as a popular grassroots political movement in the 1960s with the publication of Rachel Carson's book *Silent Spring,* deep ecology emerged as an ecological and environmental philosophy promoting the inherent worth of non-human living beings regardless of their instrumental utility to human needs. Deep ecology also led to a radical restructuring of modern human societies in accordance with such ideas (www.deepecology.org).

[19] The term I initially used was "chauvinist," with the intention of emphasizing how distorted, dogmatic, aggressive, and exaggerated anthropocentrism can become when it shapes theories and methodologies. I replaced the term chauvinist with "distorted" to avoid a misinterpretation of "chauvinist," such as gender connotations, gender discrimination, etc.

[20] This dissertation does not confront theories like feminism in relation to body materialism and cultural practices that may shape what is experienced as natural or real (Bennett, 2004). However, in order to address the question and identify relevant theories from material culture that can be utilized to inform biomimetic design, and for the sake of focusing on filling the gaps between anthropocentrism and biocentrism in relation to material culture, neither all the details nor all the theories are included here.

centered approaches may affect a design process and designs produced. Latour (1999) calls these unintended consequences “slight surprise of action” (p. 281), where events are independent of the initial intentions, and only the *doing* is emphasized, with no responsibility assumed by the actors—in this case the designers.

Another example of this anthropocentric extrapolation, is the way in which agency is used as a manifestation that places humans at the center of knowledge-making. This point is suggested in the *Actor-Network Theory*—which considers humans as “living actors” and objects and things as “dead actors” (Latour, 2005) in an interwoven net of interactions that shapes human culture. Anthropocentric arguments can reasonably suggest that only human species can write, read, and document reality, in the process of collecting and expanding our memory to external means (e.g., books, records, and artificial intelligence devices), artifacts and objects, which can be understood as part of building culture. Humans (apparently) differ from other species in the ways we achieve and process knowledge. In a strict sense, knowledge is the awareness of facts, information, and skills acquired through experience. From a biocentered perspective, knowledge is already *made*, or *in the making* in evolutionary terms, and is beyond human agency, essentially made in a non-deterministic way.[21] Long after Darwin and Wallace’s initial proposition, evolution can no longer be understood as a theory as much as a fact. So, it can be argued: What is evolution if not a process that documents life’s success and existence, and species a living corpus of that process? What is reality if it only considers one species’ reality

[21] Relativizing human agency and framing any transforming process as probabilistic or logically expected can be misunderstood as a deterministic view. The dominant view of this research project on how evolution works in the making of reality is based on scientific evidence, and does not involve a pre-determined future but a probable one among other possibilities. To human perception, a future can look pre-determined, but can only be approached probabilistically. For instance, in physics photons behave like particles and/or waves depending on the observer. It was recently discovered that photons “decide” how to behave based on information they “get” from the future (a fraction of time ahead in the future). Some theories sustain that past, present, and future is just a phenomenon experienced by animals (including humans).

(humans') as an incomplete reality? Did reality exist before homo-sapiens? Will reality exist after? These and other questions seeking to understanding material reality in relation to human culture existence were perhaps anticipated by the Lucretian interpretation of material reality in *De Rerum Natura*[22] described by Bennett (2004), which "depicts a world that preexists our [human] arrival, constitutes our present, and would endure our [human] departure" (p. 356). This Lucretian view intends to reveal the blueprints of material being, the smallest constituent parts of material (material atoms or "primordia"), and the principles of association governing them (Bennett, 2004). This view correlates with what is observed in quantum physics: atomic and subatomic particles, dark matter and the entanglement of the parts with forms of energy, which constitutes the "mix" of reality. Bennett (2004) emphasizes how cultural practices are shaped by experiencing such reality, perceiving nature through things "with the power to addle and rearrange thoughts and perceptions" (p. 348).

This research project subscribes to the—perhaps posthumanist—idea that we humans, as a very young species, are just discovering and interpreting the nature of things through human experience and evolutionary inheritance, and that reality can be framed only partially, as *our* version of reality at this particular cosmological moment.

From a biocentered perspective, plants or animals don't need to document or compartmentalize reality in order to be aware and act accordingly about what they need; they *read* reality in their own ways, ways that are generally much more sophisticated and that humans barely understand or have just started to understand better (e.g., studies on super organisms and self-organization are getting close to new answers about complex animal and plant behaviour). In

[22] *De rerum natura* (Latin: *On the Nature of Things*) is a first-century BC didactic poem by the Roman poet and philosopher Lucretius (99 BC–55 BC). Lucretius presents the principles of atomism, the nature of the mind and soul, explanations of sensation and thought, the development of the world and its phenomena, and explains a variety of celestial and terrestrial phenomena.

recent years, the more science has studied these life phenomena the more other species surprise us with what they *know*.[23] Separating humans as cultural makers from other species as "non-cultural" or "non-makers" becomes diffused when we analyze reality from an ecological standpoint. The anthropocentric superiority and sophistication assigned to human species in comparison to other species fade when reality is analyzed, taking into account the results and effects of one species upon its survival (humanity), in contrast with what other species have done for theirs; one at the high expense of depleting and exhausting the planet (which paradoxically compromises its own survival), the others giving back as much as they take with evidenced harmony and frugality, to perpetuate their existence as species. What distinguishes *Homo Sapiens* from other species is our capacity to use our developed brain to figure out complex concepts. Understanding the implication of the anthropocentrism in relation to our survival and learning from other species how to fit better on this planet, will allow us to figure out how to cope with the coming Anthropocene years.

It is important to consider that while some referents from material culture have addressed the Anthropocene more recently (e.g., Bruno Latour in his essay "Agency at the Time of the Anthropocene"), other referents' approaches (e.g., Bourdieu's and Steiner's in approaching culture-nature) were formulated before the concept of Anthropocene was introduced. The term Anthropocene was coined by Paul Crutzen in the year 2000 (Steffen, Grinevald, Crutzen, McNeill, & Rosing, 2011). It linked the concept of anthropocentrism with a new epoch, scientifically (geologically) proven only in recent years. Today the Anthropocene epoch is at the core of a contextual time frame of climate change's public agenda.[24] As Latour (2014) noticed,

[23] As an additional example, it was recently discovered that plants can "see;" they have the same photonic receptors in cells than that humans have in cells in our pigment cones in the retina (Williams, 2016).
[24] After this literature review was finished, photographer and filmmaker Edward Burtynsky launched "The Athropocene Project," with the release of the documentary *The Anthropocene* (2019). This is a strong sign of how

the “facts of geology have become news” (p. 3). Contrasting these perspectives through the lens of anthropocentrism is fundamentally useful when exploring the idea of biocentrism in the Anthropocene.

A biocentered way of thinking is a consequence of changing lenses to revise our assumptions and perspectives in relation to nature. It is about understanding life (not humans alone) as a logical result in the context of a cosmological phenomenon, and doing so placing life at the center of relevance. Nature places life at the center of relevance, and this idea contrasts, at the core, the basis of traditional humanities and most anthropocentric fields of study.

The problem with the anthropocentric interpretation of culture is not that it puts humans at the center of its perspective, but that it puts them at the center of relevance. According to the “standards of nature,” such an *eccentric* behaviour in a species might be considered odd, unconventional, and unsuitable. That is the bitter lesson to learn from the fossil records of odd animals and plants that no longer exist: adaptation and survival often imply moving off the center of relevance, to the humble periphery of a system (Benyus, 1997; Wahl, 2016; Wilson, 1984). Thus, an alternative anthropocentric approach should not place humans at the center of relevance but rather at the front-line or periphery of life’s evolution. The fundamental purpose of humankind, as with any other species, is survival, individually, collectively, and culturally. Without life conditions that connect us with all life forms, we humans will not survive.

E.O. Wilson (1984) refers to culture from an inclusive angle, in which humans and other species convergently evolve into their own forms of culture, as an evolutionary event integrated to the history of nature. Culture from this approach can be speculated as inevitable and ubiquitous to life. Thus, homo sapiens is one more species sharing a common phenomenon

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the concept is being accepted by not only the scientific and academic realms, but has reached a broader audience (https://theanthropocene.org/film/).

among other species—and this challenges the assertions of some material culture theorists. However, the differences on how this convergence is manifested varies from what is observed in anthropocentrism. For instance, Wilson compares the bioregions with no boundaries that we find in nature as a result of millions of years of evolution to the divisions that humanity has created more recently. He claims that (human) cultural evolution is only a more recent (and sophisticated) manifestation of genetic evolution.

Gibson's (1977) "Theory of Affordances" also aligns with Wilson's evolutionarily inclusive ideas, blurring the divisions between human behavior, culture, and natural responses: "An affordance cuts across the dichotomy of subjective-objective and helps us to understand its inadequacy" (p. 129). The Theory of Affordances reflects on how the quality of objects and environments allows animals (and, by extension, humans) to perform actions, framed within the relationship between natural and human environments (Gibson, 1977; Greeno, 1994). In biological terms, features like aposematism[25] and crypsis[26] affecting animal behaviour can also be studied under the idea of affordances, too.

In his book *What Is an Animal?*, Tim Ingold (1994) also supports the Theory of Affordances and Wilson's ideas, as a standpoint from which to confront the material culture status quo represented by traditional anthropologists. He questions the anthropocentric implications at the core of the culture-nature dichotomy:

> Does not the anthropological project of cross-cultural comparison rest upon an implicit assumption of human uniqueness vis-a-vis other animals that is fundamentally anthropocentric? Moreover, if we follow the promptings of modern evolutionary theory in recognizing the essential continuity between human and non-human animals, does this not entail the adoption of an ethnocentrically "Western" conception of human nature? Is

[25] In Zoology, aposematism is the use of a signal, and especially a visual signal, of conspicuous markings or bright colours by an animal to warn predators that it is toxic or distasteful (https://www.merriam-webster.com/dictionary).
[26] In Biology, crypsis is the ability of an organism to conceal itself especially from a predator by having a colour, pattern, and shape that allows it to blend into the surrounding environment (https://www.merriam-webster.com/dictionary).

> it possible, even in theory, simultaneously to transcend the limitations of both anthropocentrism and ethnocentrism? (Ingold, 1994, p. 1)

Ingold's idea coincides with Wilson's proposition of considering human culture evolutionarily linked to animal behaviour and so to nature, although he admits that there are contradictions in the Western literature. Ingold (1994) argues that "humankind is identified with the biological taxon *Homo Sapiens*, one of an immense number of animal species inhabiting the earth,[27] connected synchronically in a complex web of ecological interdependencies, and diachronically in the all-encompassing genealogy of phylogenetic evolution" (p. 5). In tune with more inclusive and less anthropocentric views of culture and nature, Joe Moran shares a new insight to cultural studies and natural sciences through *ecocriticism*, in an effort to integrate disciplines and challenge their divisions. According to Moran (2010), ecocriticism "examines the ways in which culture effects a separation from nature, producing hierarchical distinctions between the human and non-human" (p. 171). Ecocriticism criticizes the anthropocentrism by analyzing "the appropriation of nature by culture" (Moran, 2010, p. 172). Coincidentally, Moran (2010) shares the view with other thinkers (e.g., Fritjof Capra) that the anthropocentric dichotomy culture-nature (and human-nature) has historical roots in the past. These roots can be traced back to the agrarian revolution, and later in the enlightenment of the 17th century, with the dualism between mind and body proposed by Descartes as a key element in this subjugation of nature. Capra (1982) also refers to this phenomenon when he analyzes the separation of sciences-humanities as part of "a Cartesian method that has led to fragmentation, … a characteristic of a widespread attitude of reductionism in science" (p. 59), and he adds, "the Cartesian division between mind and matter has had a profound effect on Western thought. It has taught us to be aware of ourselves as isolated egos existing inside our bodies" (p. 59).

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[27] According to UNEP there are about 8.7 million species estimated. UNEP's World Conservation Monitoring Centre (UNEP-WCMC), in Cambridge, UK. See: http://www.coml.org

Jules Prown (1982), in his original article “Mind in Matter: An Introduction to Material Culture,” emphasizes and criticizes “the progressive triumph of mind over matter” (p. 2) as part of a Western conception of human history, in an attempt to propose a material culture methodology that sees [man-made] material artifacts—*matter,* as evidence of [human] culture—*mind.* Prown admits the contradictory but yet useful combination of both concepts material and culture to define a disciplinary methodology. He has examined the different etymological connotations, and associates these differences with fundamental divisions derived from anthropocentric human perception, such as the division of the universe between earth and sky. More recent voices from material culture, such as Carl Knappett (2005), have also tried to critically address the proposition of separating mind and matter: “if we are to understand the flows of matter, energy, and information, then we need to overcome this dichotomy between structure and organization, between composition and form, and between mind and matter” (p. 15).

Prown’s and Knappet’s intentions are to close the breach between mind and matter and entangle the two concepts. However, this proposition still reveals an anthropocentric angle that seems to limit these intentions by falling into another Cartesian division: separating humans from nature. In this sense, Prown explicitly suggests to exclude natural objects from the study of the artifacts of material culture, and implicitly excluding animals from the concept of culture. Prown (1982) assigns intelligence and culture only to the realms of a human-made world, contrasting for instance, Wilson’s views on “animal culture” and evolutionary intelligence. Prown (1982) claims that material culture, as a study, “is based upon the obvious fact that the existence of man-made objects is concrete evidence of the presence of a human intelligence operating at the time of fabrication” (p. 1). E. McLung Fleming (1974) shares Prown’s view, finding a basic wonder about man [human species] in “his capacity for building culture” (p. 154). Following this reasoning, and if culture is entangled with the relation animacy-inanimacy, the premises should justify other forms of culture in nature, too. Knappett (2005) introduces a possibility here, suggesting that if an organism modifies its environment for the purpose of adaptation, is it fair to think that in doing so it confers a degree of livingness and customization to its apparently inanimate surroundings. Many species in the animal kingdom are capable of making things as part of their cultures by modifying the surroundings, to their convenience, for survival; for instance, termites' cooling towers, beavers' dams, or the puffer fish's artistic circles[28] are proofs of the capacity of these animals to show cultural behaviour. In similar ways, a beehive may be evidence of bees' collective intelligence, and a spider web may be evidence of individual genetically inherited intelligence. According to evolutionary scientists such as Wilson (1984) and Carl Sagan (1977), among other inspiring scientific minds, intelligence, as well as other life features, is suggested to be convergent; so, it seems, is the case with culture.

The exclusion of natural objects from the artifacts of material culture and materials, can be evidence of how deeply rooted traditional material culture is to an anthropocentric way of knowing, perhaps as a consequence of accepting material culture as a subdiscipline of other humanities disciplines. Separating humans from nature can be interpreted as a reductionist effort for scientific legitimacy, yet under an anthropocentric influence. This in itself may represent a contradiction, and a risk that may confine material culture as a disciplinary field to the limits of isolated disciplinary egos proposed by Capra (1982), which conflicts with a more holistic and biocentered perspective.

From a biocentered perspective, human-made artifacts are also fabricated from

[28] The puffer fish of the Sea of Japan carves circular ridges on the sea floor, using only his flapping fin, tirelessly working day and night until reaching perfection. The purpose of this artistic technique is multiple: these circles intimidate predators from the distance (aposematism), but attract—like a visual sign——puffer female fish to mate on that same spot, which later turns into a nest, protecting puffer fish eggs from sea currents and predators (http://www.spoon-tamago.com/2012/09/18/deep-sea-mystery-circle-love-story/).

processing and/or transforming raw materials found in nature, in the same way birds build nests, termites build their cooling towers or spiders and worms create silk. While a biocentered perspective on material culture may sound provoking and at times naïve to the ears of those who subscribe to anthropocentric skepticism, it is also an open door to the evolution of the disciplinary field of material culture, and provides a conciliatory opportunity to mind the gaps of human-nature and culture-nature.

In this sense, the more recent reflections from Latour on agency in the Anthropocene reveal an opportunity to consider biocentrism as a bridge towards an *aggiornamento* of material culture, that conciliates one species—human—and its culture, with nature, others species, and other cultures. This may not be just an ecological effort to "recombine" the artifacts of nature and society or to establishing a contract between nature and humanity (Latour, 2014), but rather, through a biocentred lenses, to render these divisions irrelevant. Latour (2014) reveals this idea when he writes:

> Far from trying to "reconcile" or "combine" nature and society, the task, the crucial political task, is on the contrary to distribute agency as far and in as differentiated a way as possible—until, that is, we have thoroughly lost any relation between those two concepts of object and subject that are no longer of any interest any more except in a patrimonial sense. (p. 15)

The idea of the distribution of agency is present in the inclusive and more holistic characteristics of biocentrism. At the end of his essay "Agency at the Time of the Anthropocene," Latour (2014) makes strong claims that expose the limitations of material culture when facing a paradigmatic shift in human history, which may shape the future of the disciplinary field:

> Neither the extension of politics to nature, nor of nature to politics, helps in any way to move out of the impasse in which modernism has dug itself so deeply. The point of living in the epoch of the Anthropocene is that all agents share the same shape-changing destiny, a destiny that cannot be followed, documented, told, and represented by using any of the older traits associated with subjectivity or objectivity. (p. 15)

Despite a fundamentally bitter and pessimistic description of human reality from material culture criticism (particularly from Latour, but also Ingold and Bennett, among others), the prospect of biocentered methodologies, such as biomimicry, is an optimistic one based on discovering and rediscovering the successful "design stories" of nature. Biocentered thinking offers an opportunity to advance the disciplinary fields of design and material culture into a new terrain that connects them by redistributing agency and reinterpretating the coupling of material-culture.

The future of material culture depends on its evolution as a disciplinary field that does not pursue some protected niche within the domains of other disciplines (Miller, 2008), but rather takes risks in looking at the fundamentals that connect the field with other fields, the discipline with other disciplines, inside and outside the man-made world. Bennett (2010) in this sense has emphasized the need to interpret material from a view that opposes anthropocentrism and contrasts "the narcissism of humans in charge of the world" (p. xvi). Perhaps this can be achieved through biocentered thinking, and in favor of an anthropomorphic[29] idea of human agency echoing non-human nature (Bennett, 2010).

Material culture has contributed to knowledge through methodologies that have incorporated scientific methods to close the breach between theory and practice. Despite significant challenges posed by anthropocentric limitations, material culture has provided a better understanding of the essential concepts that define matter, materials, materiality, animacy, inanimacy, human culture, and the connecting neural factors that keep these concepts entangled. A biocentered angle to this methodology may enrich the field, and incorporating such an angle with the material culture discourse could be understood as a sign of an evolutionary path and disciplinary maturity.

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[29] Anthropomorphism is an interpretation of what is not human in terms of human characteristics (i.e., treating another species in the way we treat our own, aligning human nature to non-human nature).

2.1.3 Human Ecology Domain

2.1.3.1 Human Ecology and True Ecological Humanity

Human ecology can create an inclusive space for agency and transformation towards biocentered practices, in tune with the idea of generalist practitioners (Papanek, 1984; Strauss, 1990), and in line with radical human ecology (McIntosh, 2012). Human ecology is defined as "the scientific and holistic study of human beings, their environments, and human-environmental interactions" (Westney, Brabble, & Edwards, 1988, p. 129). Human ecology can be understood as both a science and an art due to the more holistic cross-disciplinary characteristics of its theory and practice. In human ecology, similarly to design disciplines, theory and practice cannot be separated (Westney et al., 1988). To understand what human ecology stands for, it is useful to look at the etymological aspects of the terms *ecology* and *human*. First, the term *ecology* is rooted in the Greek *oikos,* meaning household; it is the study of the relationship between organisms and their environments, and it represents the idea of contextualization to the discipline (Visvader, 1986). Second, the term *human* refers to the agency of individual beings but also to the collective as a species (*Homo Sapiens*); the nature and consequences of human behavior become the central point of human ecology studies (Visvader, 1986). Human ecology is the study of human nature and its relationship with its environment. Visvader (1986) defines human ecology as "a pluralistic approach to a series of nested, interrelated and overlapping questions concerning the relation between humans and their environment," and adds that "it is interdisciplinary in nature and yet not a discipline itself in the usual sense" (p. 125). Human ecology may seem a modern and unconventional discipline; however, studying the relationship between human beings and nature is "a subject matter as old as human culture itself" (Visvader, 1986, p. 125). The understanding of nature and culture is at the center of the definition of human ecology.

The way we understand these key concepts may change the way we understand this more holistic discipline. Thus, in these terms, human ecology could perhaps represent either an anthropocentric or a biocentered way of knowing and thinking. For instance, Visvader (1986) points out that “given certain [anthropocentric] values and goals, our [human ecology] strategies can be mistaken” (p. 127), and thus, relaying on technological fixes may lead to deeper ecological problems. To correct this, Visvader (1986) claims “nature cannot help us, we have to help ourselves” (p. 127), as if nature and humans belong to two different realities. The statement implies that we should be separating nature from ourselves. This reveals a common anthropocentric limitation in the way humans can be seen in relation to nature. A biocentered approach to the same formulation may claim that indeed nature *can* help us, *if* we help ourselves, and truly helping ourselves is about helping nature. A human-ecologist, biocentered approach is manifested in “The Challenge of Radical Human Ecology to the Academy” by Alastair McIntosh (2012), who sees human ecology in its “widest and most holistic sense,” which he describes as “looking at the cosmologically sustained planet as the ‘household’ in which we live” (p. 36). This latter approach offers the potential to connect human ecology to design, and design to science on the biomimicry “playground.”

2.1.3.2 A Biocentered Human Ecology

A biocentered way of thinking proposes changing our lens to revise our assumptions and perspectives in relation to nature. It is about understanding life (not humans alone, and eventually not life in this planet alone) as a logical result in the context of a cosmological[30] phenomenon and, by doing so, placing life at the center of relevance as nature does. At the core,

[30] According to NASA, the definition of cosmology is “the scientific study of the large scale properties of the universe as a whole.” As a branch of philosophy, cosmology deals with the origin and general structure of the universe, with its parts, elements, and laws, and especially with characteristics such as space, time, causality, and freedom. The understanding of life is intrinsically affected by this way of knowing.

this idea contrasts with the basis of the humanities and most anthropocentric fields of study. But it is important to avoid unnecessary conflicts about this idea. Nature should not oppose the business of humanity, nor should the humanities disconnect humans from nature. From a cosmological perspective, humans are entangled within a system that connects all living things with their purposes and their cultures. Contrary to what many may think, connecting to nature on a personal or collective level is a simple business that does not demand any physical effort. You don't need to go hiking every day, swim in a lake every morning, or move to a cabin in the middle of the forest to achieve this connection. While all these outdoor activities are enjoyable and will undoubtedly enable you to experience nature through your senses at a different level, our human mind can also find that every moment of our lives, independently of where or what we do, we are connected to nature. If you can feel yourself breathing, moving, thinking, and interacting with other life forms (such as people), you are the evidence of life and nature in action.

2.1.3.3 Turning Point and Shifting Paradigms

Humankind in the Anthropocene epoch—fully described in Section 2.2 (Steffen et al., 2011)—has progressively evolved towards detachment from nature if not completely at the physical level (as if this would be possible), at least in the mind. This also suggests that there is a separation between mind and matter (Prown, 1982), an idea that is explored as a metaphysical discussion in the realms of human ecology (Williams, Roberts, & McIntosh, 2012). This detachment has been describing by Gregory Bateson (1972), Fritjof Capra (1982), David Orr (2002), and other intellectuals, as an indication of a tipping point or a turning point in human history. Under a biocentered view, this tipping point can also lead to a moment of realization, in which humans have to react, recalibrate, get back on track to a "regenerative mode" (Wahl, 2016), and re-connect to the natural ways that give us chance for a sustainable future. Reconnecting implies a precondition of dis- or misconnection, not only with the rest of nature, but also within different generations of humans, due to the speed of information retrieval and the speed of knowledge processing, to the detriment of the pace required to achieve wisdom (Orr, 2002). As mentioned in Section 2.1.2, Dieter Steiner's (1995) view, which is consistent with mainstream ecocriticism views, is that in "recognition of an ecological crisis" (p. 35), the intergenerational disconnection we experience as development or modernity, and the loss of wisdom present in anthropocentrism, is the cause of an "evolutionary inversion" in humanity (p. 42): "If a system based in younger phenomena does not have a mutually influencing relationship with the systems associated with older phenomena, but begins to entirely dominate them, then we have a clear case of evolutionary inversion" (p. 42).

Two decades before Steiner, Gregory Bateson (1972) referred to these disconnections as part of the dynamics of an ecological crisis. Bateson recognized that from a human ecology standpoint, humanity was facing a crisis of detachment from nature. This realization is key to understanding the role that human ecology can play as an agent of transformation, facilitating the discipline's evolution from its anthropocentric roots to biocentered inclusiveness.

In his book *Designing Regenerative Cultures*, Daniel Wahl (2016) explains the regenerative process in progress that involves transforming anthropocentric into biocentered or life-centered—and, ultimately, integral—practices. The transition that Wahl describes situates emerging disciplines like biomimicry, and transforming disciplines like human ecology, at a shifting point in the dominant design paradigm.[31] Guba (1990) and Nielsen (1990) refer to this turning points as part of the cycling process introduced by Thomas Kuhn in 1962, as history repeats itself in a similar fashion every time humanity faces a deep planetary crisis. According to Kuhn (1996), a paradigm shift is a change in basic assumptions within the dominant theory, predominantly ruled by science.

[31] Ergon Guba (1990) in *The Paradigm Dialog* defines paradigms as "a set of basic beliefs that guide actions" (p. 17).

Kuhninaapproach suggests that there are certain conditions that need to be filled in order to recognize when a paradigm shift is complete. This is linked to his proposed structure of the three phases of a paradigm shift: a pre-paradigm phase, a normal science phase, and a revolutionary phase (Kuhn, 1996). Kuhn proposes this structure as a cycling or evolving loop idea (Fig. 2.01). Science eventually may go through these cycles repeatedly (Kuhn, 1996). From a design standpoint, this axiological interpretation of a Kuhnian paradigm shifting/cycling model has influenced the way design philosophers see technological paradigms that account for continuous and discontinuous innovation and disruptions in anthropocentric times (Crilly, 2010).

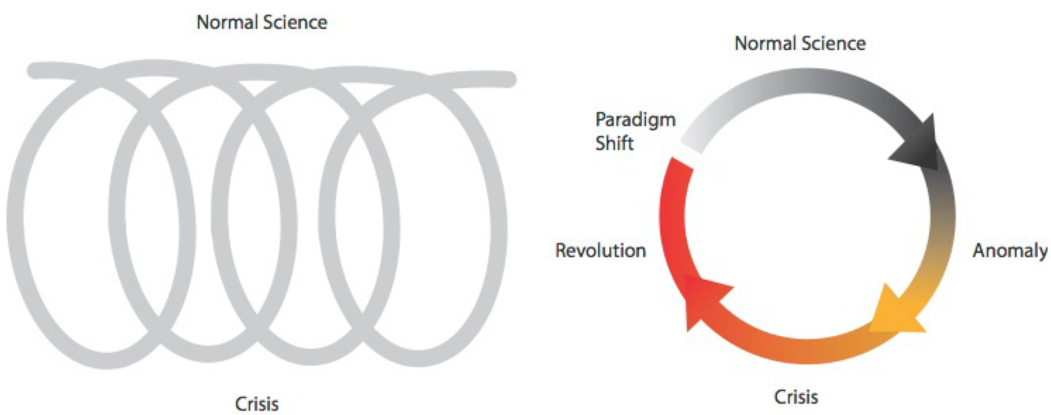

Figure 2.01. The cycling structure of a paradigm shift process proposed by Kuhn (Fiorentino & Montana-Hoyos, 2014).

Guba (1990) and Nielsen (1990) suggest that our current worldview is dominated by three overarching knowledge paradigms: post-positivism, critical-idealism, and constructivism.[32] It is not a simple task to place either transdisciplinary or interdisciplinary spaces proposed by

[32] In its broadest sense, positivism is a rejection of metaphysics. It is a position that holds that the goal of knowledge is simply to describe the phenomena that we experience. From a positivist standpoint the purpose of science is simply to stick to what we can observe and measure. Knowledge of anything beyond that, a positivist would hold, is impossible. Positivism was strongly embraced by the industrialism in the 20th Century. Critical realism is one of the most common forms of post-positivism. A critical realist believes that there is a reality independent of our thinking about it that science can study. Positivists were also realists. The difference is that the post-positivist critical realist recognizes that all observation is fallible and has error and that all theory is revisable. The critical realist is critical of our ability to know reality with certainty. Another form of post-positivism is constructivism. Constructivists believe that we each construct our view of the world based on our perceptions of it. Because perception and observation is fallible, our constructions must be imperfect. (http://www.socialresearchmethods.net).

human ecology, sustainability, or biomimicry within the boundaries of these suggested paradigms, nor to classify them under any clear disciplinary label. Instead, the idea of playing a role within an open "paradigm dialog" in which commensurable or blending knowledge paradigms can be pragmatically applied to multiple disciplines (Lincoln & Guba, 2000) seems a better fit with the realms of transformative disciplines like human ecology and emerging design disciplines like biomimicry. In this context, the emergence of biocentered disciplines (such as biomimicry) might be seen as part of the transition to a pre-paradigm phase in which there is no consensus yet on any particular theory; nonetheless the research being carried out could be considered scientific in nature (Kuhn, 1996). (Fig. 2.02.)

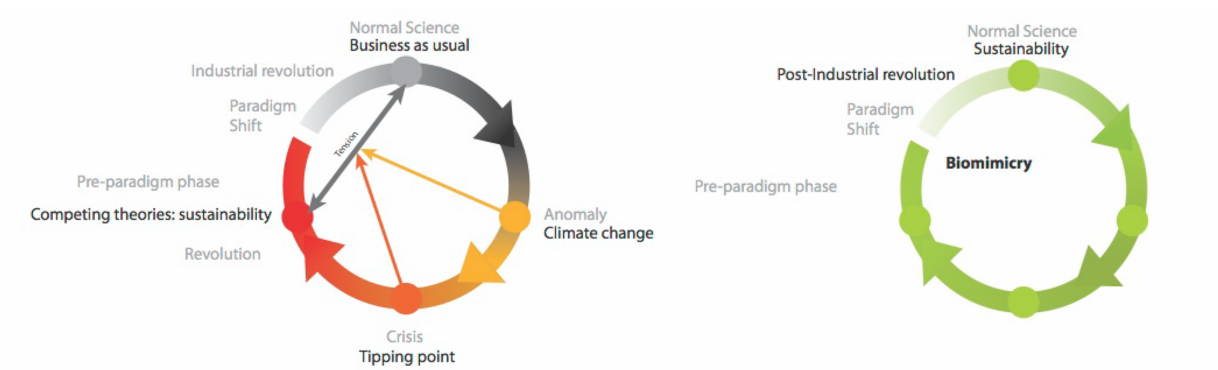

Figure 2.02. Emerging disciplines like biomimicry in a pre-paradigm phase, the paradigm shift, and the future normal science. In this example the anomaly and crisis are represented by climate change and its consequences, and the pre-paradigm phase by sustainability theories. Biomimicry is situated as a response in the transition of a paradigm shift (Fiorentino & Montana-Hoyos, 2014).

2.1.3.4 Generalism and Specialization

A transcendental characteristic that connects both a human-centered discipline like human ecology and a biocentered discipline like biomimicry is the idea of generalism. Victor Papanek (1984) defines [design] generalists as those reflective practitioners who are inclined to engage messy but crucially important problems. Being a designer creates the opportunity to be a generalist. Coincidentally with human ecology, design, by its nature, must work across disciplines, and being a generalist confers an advantage. A generalist designer has a broader view from which to understand the sources of the problems before moving forward and trying to solve them. In defining *wicked problems* (described in Section 2.1.1.2), Richard Buchanan (1992) also defines design as “an integrative discipline” (p. 18), emphasizing integration as another aspect of design generalism. There is a convergence of ideas between design and human ecology at this point. According to Donald Strauss (1990):

> The discipline of human ecology seeks to understand and manage wisely the complex problems of the planet of which humans are a part. It integrates the old disciplines of highly specialized scientific investigation with the new discipline of seeing things, and acting upon them, as generalists. (p. 22)

Strauss (1990) defines human ecology as a *metadiscipline*, in which “human ecologists possess the attributes of specialist and generalist in beautiful balance” (p. 23). Dieter Steiner (1995) emphasizes the integrative scholarship capacity of human ecology, creating the space for diverse perspectives—usually fragmented—under a common ground. Steiner (1995) proposes four dimensions of integration: the transdisciplinary, the transcientific, the evolutionary, and the transpersonal dimensions. The transformative character of human ecology is implicit in all of them. Both design and human ecology share this convergence, and the potential space for synergies. Both are also disciplines in need of evolving from an anthropocentric disciplinary fragmentation to a balanced and more holistic practice, centered on “the specialty of generalizing” (Strauss, 1990, p. 1).

A biocentered way of thinking and a multidimensional methodological approach may strengthen this convergence. StrC, the project that is the focus of this dissertation, is a good example of how this convergence can make a significant contribution to knowledge. Learning how the natural systems work, as proposed by biomimicry and by the StrC, may create synergies for generalists to thrive and for excessive fragmentation and overspecialization to diminish. Observing and learning from nature about how specialization and overspecialization operates among species and ecosystems may give some important clues. In *The Ghost in the Machine*, Arthur Koestler (1967) calls this phenomena “blind alleys” in evolution (p. 161). According to Koestler, overspecialization in nature is the principal cause of stagnation and extinction:

> Take, for example, that charming and pathetic creature the koala bear, which specializes in feeding on the leaves of a particular variety of eucalyptus tree and on nothing else; and which, in lieu of fingers, has hook-like claws ideally suited for clinging to the bark of the tree—and for nothing else. Its human equivalent—minus the charm—is the pedant, the slave of habit, whose thinking and behavior move in rigid grooves. Some of our departments of higher learning seem expressly designed for breeding koala bears. (Koestler, 1967, pp. 161−162)

The koala bear analogy remains valid half a century after Koestler wrote those words. Overspecialization is a risk driven by compartimentalism, and by “narrow specialisms, and mediocrity of meritocratic western capitalist bureaucracy and division of labour” (Ortega y Gasset, as cited in Moran, 2010, p. 12). This has been also remarked upon by philosophers such as Bacon and Nietzche (Moran, 2010). Joe Moran (2010) refers to this phenomenon as the “anxieties about specialization” (p. 4), specially created from academia, but also extending to professional practices. Moran points to the times of Aristotle, to remind us that these anxieties were not always defining the dominant paradigm, and that the very word “university” originates in the Latin word *universitas,* meaning “universal” and implying a more holistic approach to learning, and an apprehension to the general studies or *studia generalia*, which is at the root of the idea of generalism. *Philosophia*, which comes from Greek and means “love of wisdom” (McIntosh, 2012), was—and it still is—calling to this wise, fundamental idea of generalism. Philosophy transcends more specialized forms of knowledge, and suggests undisciplined knowledge (Moran, 2010). According to Moran (2010), disciplinary spaces moving to interdisciplinarity is a response to these “anxieties about specialization” (p. 4).

As observed in the previous section, ecocriticism uses the concepts of “bioregion” and "biodiversity" when defining boundaries between disciplines. E. O. Wilson (1984) and other environmentally conscious biologists were associated with the concept of bioregions: according to Wilson, a bioregion is "a self-sustaining area which cannot be contained within the normal political boundaries established by local or national governments" (as cited in Moran, 2010, p. 174). Within these areas "a whole diversity of species coexists and depend upon each other for survival" (Wilson, as cited in Moran, 2010, p. 174). These bioregions suggest ambiguity or blurriness at the boundaries, consistent with what Moran proposes for interdisciplinarity:

> …ambiguity is partly reflected in the slipperiness of the term, "interdisciplinary." It can suggest forging connections across the different disciplines; but it can also mean establishing a kind of undisciplined space in the interstices between disciplines, or even attempting to transcend disciplinary boundaries altogether. (Moran, 2010, p. 15)

In natural ecosystems, the boundaries of a bioregion are where the action happens, for instance in *riparian* zones.[33] Biomimics call these interface areas the "ecotones" (Benyus, 1997). Also inspired by nature, Friederick Steiner (2002) describes this phenomenon in the human context too, when distinct habitats intersect, in, for instance, public and semi-public spaces as well as in the urban and built environments; he defines ecotones as "spatial areas of interaction" (p. 48). The transformative character of human ecology (D. Steiner, 1995), if truly and thoughtfully applied, aligns with the epistemologies of design, sustainability, and biomimicry in that all are interdisciplinary fields that tend to push or remove boundaries, and the boundaries are where innovation, change, and transformation happen in a generalistic fashion.

2.1.3.5 Criticism: Human Ecology—In Need of True Ecological Humanity

If human ecology has the potential to play an important role in projecting a post-

[33] A riparian zone or riparian area is the interface between land and a river or stream. Riparian is also the proper nomenclature for one of the 15 terrestrial biomes of the earth. Plant habitats and communities along the river margins and banks are called riparian vegetation, characterized by highly adapted hydrophilic plants (http://aep.alberta.ca/lands-forests/grazing-range-management/riparian-areas.aspx).

anthropocentric future, and if more holistic, generalistic, and interdisciplinary qualities characterize it, why are voices within the discipline still claiming an ongoing epistemological crisis? The key is, again, the current paradigm deeply rooted in anthropocentrism in contrast to other disciplinary fields moving out of it. In “Radical Human Ecology,” McIntosh (2012) argues that the main challenge for human ecology is an onto-epistemological one, suggesting that it is necessary to add a metaphysical angle to move from a dominant epistemology rooted in the Western modern paradigm:

> In Human Ecology terms... there is also a growing awareness that the problems and crises are interrelated because they have the same root cause: the almost totalizing dominance of the particular assumptions, worldview and social practices of the modem paradigm. (Goodman, as cited in McIntosh, 2012, p. 40)

According to McIntosh (2012), characteristics of this dominant situation in human ecology include “the narrowness of disciplinary compartmentalization of knowledge,” “the exclusion of generalist contextualizations,” and “the one-sided scholar’s recognition hunkering down into the sheltered disciplinary hole of specialization” (p. 40) as characteristics of this dominant reality in human ecology:

> What doesn’t work in either human or ecological terms is to treat the world as a globalized homogeneous market surface. That sees commodities but misses the cosmology. It is incapable of comprehending soul and where this spirit dominates within academia, it is doomed to self-deconstruction up the ivory tower. Radical Human Ecology therefore queries much of contemporary academia. (McIntosh, 2012, p. 35)

McIntosh strongly aligns with a so-called “environmentalist” view, although it is more accurate to insist that this epistemological direction is closer to a process moving away from anthropocentrism and closer to biocentrism:

> For many, an expression like "the social construction of nature" is just a generalized way of saying that humans have an impact on nature (2012, p.46). […] The loss of contact with nature, a biophilic deprivation, must lead to pathology (Shepard as cited in McIntosh, 2012, p.45). […] Could we be touching on epistemological problems with which most western thought has not come to terms, but which the ecological crisis now presses on us globally as never before? I consider that radical Human Ecology is an

> irritation to the Academy precisely because it raises such elephant-in-the-living-room questions, and does so, unlike most academic analysis, in ways that touch the visceral of us all (McIntosh, 2012, p.51).

A biocentered approach aligns human ecology towards a paradigmatic shifting moment in human history. Human ecology in this sense creates an inclusive space for agency and transformation, in tune with the idea of generalist practitioners, and in line with radical human ecology as “a key philosophical role to play in bringing the condition of the world to bear on the structure of knowledge” (McIntosh, 2012, p. 33). The synergies and commonalities between human ecology, design disciplines, and biomimicry help create the conditions for an evolutionary path from anthropocentric to biocentered perspectives.

2.2 Philosophical Foundations: Sustainability and Biocentered Thinking

This section situates biocentered thinking as a means to achieve sustainable ways of design. This discussion is relevant for designers looking for sustainable innovation through the implementation of a biomimetic methodology. Such discussion requires understanding, first, what the concept of sustainability entails, and second, the anthropocentric context in which new concepts arise as disruptive innovation.

Both design and sustainability must be framed in the context of a new understanding of systems and structures that rule the natural world. Human society must be part of those systems and structures (Jantsch, 1980). Design for sustainability (DfS) should propose a process of design that creates the necessary framework to develop products of design or to modify human behaviour by design. Design practices should move towards a regenerative idea of design (Wahl, 2016) that modify the deeply unsustainable situation of design practice and industry, and in the process meet the aims of sustainable development. Victor Papanek (1984) wrote that

> …if design is to be ecologically responsible and socially responsive, [it] must be revolutionary and radical in the truest sense. It must dedicate itself to naturethe process natural world. Human society must be part of those systems and structures entation of a

> biomThat means consuming less, using things longer, and being frugal about recycling materials. (pp. 344–346)

David Orr (1992) agrees with this idea, adding that "sustainability depends on replicating the structure and function of natural systems" (p. 33). The following pages describe the roles of sustainability, biocentered thinking, and biomimicry as philosophies that are foundational to biocentered design.

2.2.1 Sustainability: From Anthropocentrism to Biocentered Thinking

Sustainability is a prospect—a long-term goal that can be achieved only if we move from degenerative and anthropocentric practices to regenerative, biocentered, and integral human practices (Wahl, 2016). More than 30 years after it was proposed in 1987 by the Bruntland Commission to address the prospect of sustainable development (World Commission on Environment and Development, 1987), the definition of sustainability has been consistently and recurrently accepted, and yet contested across disciplines (McIntosh, 2012), regardless of how it has been understood and used. The initial model associated with this concept that characterizes the dominant systems (based on a paradigm from economics) is called *the triple bottom line*, a multidimensional approach that adds two more dimensions (the "social" and the "environmental") to the "economic" bottom line (Fiorentino & Montana-Hoyos, 2014). Design for sustainability implies a process of design that might meet the aims of the Bruntland report's multidimensional idea regarding sustainable development (Montana-Hoyos & Fiorentino, 2015). This process creates the necessary framework to develop products of design or modify human behaviour by design. Despite today's acceptance and extensive use of this polysemic word, the term sustainability has epistemological, etymological, and ontological limitations (Boenhert, 2012; Fry, 2003), as well as an intrinsically anthropocentric nature.

Sustainability's anthropocentric limitations have been addressed by important voices of criticism included in this review (e.g., Capra, 1982; Fry, 2017; Orr, 2002, 2004; Hawken, 2014; Wahl, 2016). Such criticism may show signs of intellectual enervation towards sustainability, as Tony Fry (2017) claims "to continue with business as usual with a few token gestures toward 'sustainability' is frankly a disposition of collective stupidity" (p. 100). It may also show signs in favour of a biocentered approach, as Paul Hawken (2014) claims, "If you are decreasing life on the planet, don't talk to me about sustainability."[34] These two examples represent a change in the tone of critics, from a more tolerant and optimistic position on the prospect of sustainable development, to a more radical and skeptical position after three decades of abundant rhetoric, a position that implies more effective actions towards truly sustainable ways of "meeting the needs of the present without compromising the ability of future generations to meet their own needs" (World Commission on Environment and Development, 1987, p. 11). Daniel Wahl (2016) refers to the ambiguity of sustainability, applying the *Three Horizons* thinking model[35] (Sharpe, 2013; Fig. 2.03) to analyze how sustainable innovation can be evaluated under a degenerative culture view and a regenerative culture view (also known as the "Janus Effect").

[34] Hawken, P. (2014, December 11). Interview by Joel Makower [video]. VERGE SF Conference, San Francisco, CA. Retrieved from https://www.greenbiz.com/video/how-undo-damage-industrial-age-biomimicry/
[35] *Three Horizons Thinking* (Sharpe, 2013) "offers a methodology and practice seeing things from multiple perspectives and valuing the contribution that each perspective makes to the way we bring forth the world together" (Wahl, 2016, p. 57).

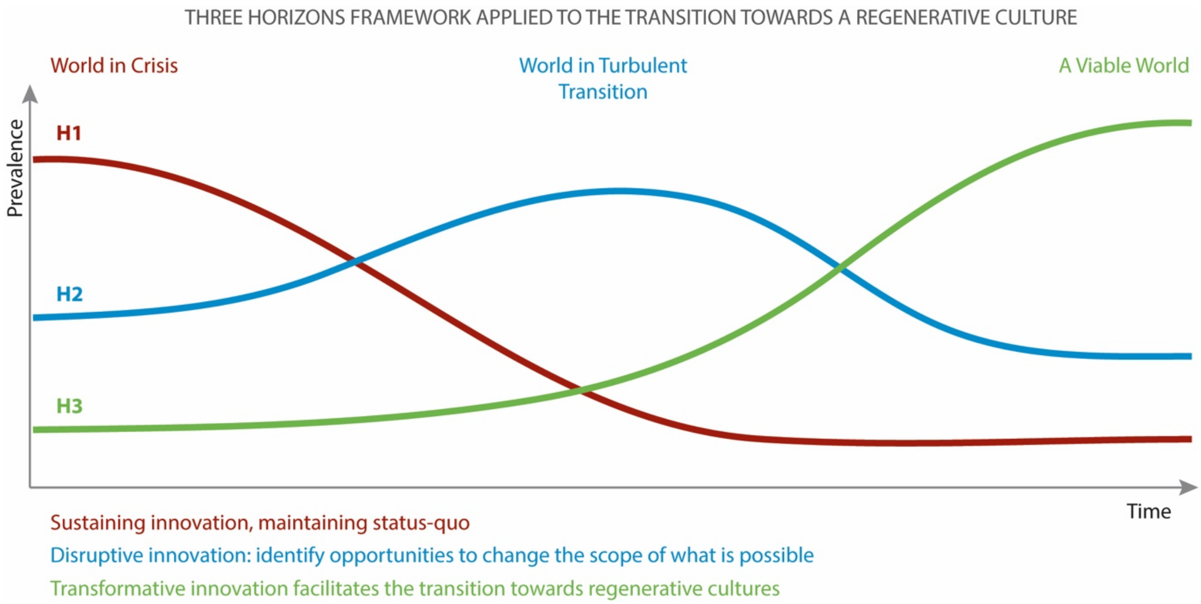

Figure 2.03. Three Horizons framework diagram (Sharpe, 2013; Wahl, 2016).

In this model, prevalence and time are the two variables used to evaluate the influence of innovation under the two views, where “horizon 1(H1)” represents the short-term, “horizon 2 (H2)” the mid-term, and “horizon 3 (H3)” the long-term (Sharpe, 2013; Wahl, 2016). While supporting H1 seems more reasonable and attuned to our current design paradigm, it only solves symptoms of sustainability “to maximize short-term benefits for isolated parts” (Wahl, 2016, p. 58). H3 instead implies “transforming causes and meaning while aiming to optimize the whole” (Wahl, 2016, p. 58). This kind of innovation takes much longer to deliver results; however, these results prevail over time. The mid-term approach, H2, can either tend to disrupt H1’s “business as usual” or build bridges towards H3’s perspective. When sustainability favours the first approach (H1), innovation is short-sighted and incomplete. If the second approach is chosen, sustainable innovation helps the transition to H3, to long-term effective solutions.

There is a growing consensus on calling the current epoch “The Anthropocene Epoch,” based on scientific (geological) evidence. The concept of sustainability has evolved over the past decades, during a period in the history of the planet when one species—human—has the main incidence of survival of all life and ecosystems (Crutzen, 2006; Latour, 2014). Anthropocentrism is essentially a human-centered perspective rooted in Western thinking and has been dominant in human history. The center of human perspectives, however, has changed several times throughout history depending on the available knowledge in different periods. For example, the Ptolemaic geocentric model of the solar system proposed in ancient Greece—which placed not the sun but the earth at the center—was replaced by Copernicus' heliocentric model[36] in the 16th century. Against our perception and common sense based on what we experience—that the sun spins around us every 24 hours—the heliocentric model we know now is the correct one to describe the orbital solar system. Similar to geocentrism, anthropocentrism, as a human-centered view, also situates humans alone at the center of relevance, and considers the world in terms of only human values and experiences. This view, as with other views in the past, can also shift when it is influenced by new knowledge about how natural systems respond to the laws of physics.

Similar to what geocentrism meant to heliocentrism in the 16th century, from a biocentered perspective, anthropocentrism can be seen today as an incomplete and problematic view in need of completion and change. Anthropocentrism can also be seen as the major cause that compromises the future of our civilization and the balance of current ecosystems that inhabit the planet (Capra, 1982; Naess, 1973; Sterba, 2011; Taylor, 1983, 1986, 2008). The way we anthropocentrically create, produce, and consume industrialized material goods and services has led to an environmental crisis, and design disciplines have key responsibilities in this situation (Fry, 2003; McDonough & Braungart, 2002; Naess, 1973; Orr, 2002; Taylor, 2008). Seminal

[36] Both the Ptolemaic and Copernican models tried to explain not only observed celestial mechanisms like the solar system, but also how these mechanisms were the center of the universe. Thus, both were fundamentally incorrect. The difference with Copernicus' proposition is that a heliocentric system is rather incomplete rather than completely incorrect.

environmental voices have criticized for decades the dominant anthropocentric linear and short-term-oriented means of production, and have advocated for a circular and long-term system to replace it (Daly, 1996; Hawken, 1994; Hawken, Lovins, & Lovins, 2013; McDonough & Braungart, 2002; Orr, 2004). Following the same line of reasoning, other influential voices from design, material culture, philosophy, and science have agreed that the standards we use to design objects, artifacts, built environments, urban spaces and whole systems have become unsustainable (Bateson, 1972; Buchanan, 1992; Capra, 1982; Fry, 2017; Maldonado, 1972). In connection to the area of interest of this research project, the way colour is produced in products and the built environment belongs to this unsustainable paradigm represented by anthropocentrism.

These assertions imply that moving from anthropocentrism to a more integral view is crucial for the survival of the species, including *Homo Sapiens*. The work of many authors analyzed in this review suggests (explicitly or implicitly) that we may be at the verge of changing or completing a human-centered perspective (anthropocentrism) into a life-centered perspective (biocentrism; Fig. 2.04).

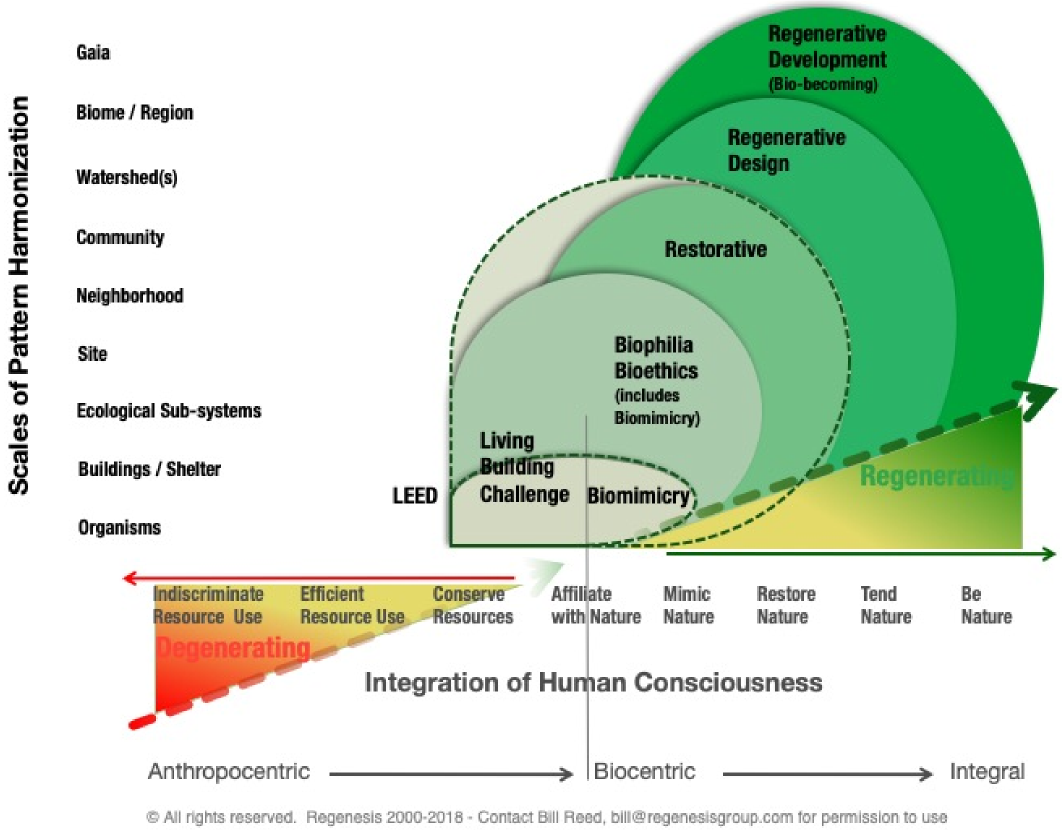

Figure 2.04. Process from degenerative anthropocentric to regenerative biocentered and integral practices of design. Diagram originally created for disciplines of built environment design (Mang & Reed, 2012).

2.2.2 The Virtues of Biocentered Thinking

Current anthropocentric design practices may be in transition to *biocentered* design practices, from linear systems to circular systems, from unsustainable design to design for sustainability (Montana-Hoyos & Fiorentino, 2015), and from degenerative to regenerative design practices (Wahl, 2016). In new methodologies rooted in biocentered approaches such as biophilic design (Kellert et al., 2008) and biomimicry (Benyus, 1997; Harkness, 2002), we can see the building blocks of emerging design disciplines, and a common disciplinary *ethos*. Literature to understand the phenomenon of the emergence of biocentered design disciplines can be traced back to foundational concepts and relevant theories inspired by nature, such as

Biophilia[37] (Wilson, 1984), Deep Ecology (Naess, 1973), Autopoiesis (Varela et al., 1974), Affordances (Gibson, 1977), Biocentrism (Taylor, 1983) and Constructal Laws (Bejan & Zane, 2012).

Biocentric theories may play a critical role in inspiring new means of creation, fabrication, production, and distribution aligned with a circular economy,[38] and in encompassing the transition from the anthropocentric paradigm to a regenerative stage. These theories may also ultimately lead to a sustainability paradigm. However, a necessary differentiation must be introduced here between *biocentric* design and *biocentered* design. The first may rely on philosophical roots, metaphysical implications, and beliefs to develop a design concept independently from a specific methodology, and with the intention of reconnecting the human mind with nature. In a user experience (UX) assessment, for instance, user-*centric* design implies thinking about the user independent of (and not necessarily acting upon) products and services, whereas user-*centered* implies that the assessment of products and services is focused on the user's interaction with those products and services. *Centered* implies a practical aspect based on praxis and reflective practice, emphasizing the practicality aspect of the biocentric outlook (Sterba, 2011; Taylor, 2008). It may rely on evidence-based scientific methodology to set the design process, which may lead to a design concept independent of subjective beliefs, and may reconnect the way humans create with the way nature creates (Capra, 1996, 2010; Wahl, 2016).

In contrast to anthropocentrism, biocentrism can be seen as an ethical point of view that extends inherent value to all living things, not only humans, in order to contribute to sustainable

[37] The term biophilia was coined by psychologist Erich Fromm in *The Anatomy of Human Destructiveness* (1973), a few years before Wilson elaborated on the theory.

[38] The circular economy model proposes a regenerative system (Wahl, 2016) in which resource input and waste, emissions, and energy leakage are reduced or eliminated by slowing, closing, and narrowing material and energy loops (see: https://www.ellenmacarthurfoundation.org/circular-economy).

futures. This notion also has philosophical roots in biocentric egalitarianism (Sterba, 2011; Taylor, 1983, 1986, 2008) and the belief that there is fundamental dignity in humanity appreciating nature (Kant, 1999; Leopold, 1970: Naess, 1973: Orr, 2002).[39] It is worth emphasizing the practical significance of accepting the biocentric outlook (Taylor, 1983) instead of confronting it. While biocentric egalitarianism sets a framework mindset that applies a moral concept to all livings things, the belief in a fundamental appreciation of nature suggests that all moral agents are required to adhere to an above all responsibility to dignify nature. Criticism of Leopold, Taylor, Naess, Spinoza, and other thinkers aligned with this line of reasoning runs parallel to the criticism of biomimicry, in that it has been misrepresented in much the same way as the concept of understanding nature as "the framework mindset" to inspire human design (i.e., nature as model, measure and mentor; Benyus, 1997).

A biocentered perspective may not be exempt from failings or blind spots, limitations, weaknesses, and contradictions. Among the critics of biocentrism, we find contrasting and reluctant voices such as Stephen Vogel (2003), Richard Watson (1983), and Gene Spitler (1982). To the views of these intellectuals, biocentrism, biocentered disciplines or biomimetic design are all humanist naïve expressions, free of skepticism and scientific rigour. Watson (1983), for instance, considers biocentric arguments by Naess and Spinoza "bound [biased] by Judeo-Christian-Platonic-Aristotelian notions of human goodness," and argues that "to call for curbing man is like trying to make vegetarians of pet cats" (p. 255). The discussion around legitimizing a biocentric perspective is an opportunity to disambiguate possible reductionist interpretations of biocentrism, and the idea of "humanism under a different guise." It is also an opportunity to

[39] *Practical Philosophy* (1999) is the first English translation of all of Kant's writings; Kant (1724−1804).

propose the possibility of considering a biocentered approach as a kind of post-humanist position.

Criticism of Taylor, Spinoza, and other theorists in support of a biocentric perspective has changed, however, in the last three decades, with the consolidation of biocentered disciplines like biomimicry and with biomimetic research being backed up by scientific methods.

2.2.3 The Idea of Biomimicry

In response to the need for revolutionary and radical new design approaches, biophilic, bio-inspired and bio-informed design concepts have emerged and thrived in recent years, ignited by the appealing and eloquent voices of biomimicry as a biocentered approach to design. As a precedent of biocentered design ideas, engineer Otto Schmidt coined the term *biomimetics* in the 1950s, to define the study of the formation, structure, or function of biologically produced substances and materials to apply in engineering materials and products (Harkness, 2002). The Biophilia theory (Wilson, 1984) came three decades later and proposed emphasizing our "inherent human inclination to affiliate with natural systems and processes, especially life and life-like features of the non-human environment" (Kellert et al., 2008, p. 3). The biophilia approach was later supported by scientific evidence that contact with nature has strong positive effects on human beings, in terms of healing from diseases, productivity at work, et cetera (Montana-Hoyos & Fiorentino, 2015). Biophilia inspired the concept of biomimicry, described as "design innovation inspired by nature" (Benyus, 1997); and biophilic design (Kellert et al., 2008), described as an "innovative approach that emphasizes the necessity of maintaining, enhancing and restoring the beneficial experience of nature in the built environment" (Kellert et al., 2008, p. 5).

Today, biomimicry (also called biomimetic design) is an emerging discipline recognized as "a leading methodology with the ability to drive environmentally sustainable innovation" (Kennedy, Fecheyr-Lippens, Hsiung, Niewiarowski, & Kolodziej, 2016, p. 46). Biomimicry proposes learning from nature rather than exploiting it as a resource. Biomimicry (from *bios*, meaning life, and *mimesis*, meaning to imitate) studies "nature's genius" and consciously emulates life's principles of adaptation and survival, mimicking form, function and/or structure as well as processes and ecosystems (Benyus, 1997), using a systems-level approach. A systems-level approach means a networked rather than linear way of fabrication. It may also entail a regenerative idea where, as in nature, instead of only consuming raw materials, closed loop systems also embrace the production of materials (Wahl, 2016). These systems have been shaped by natural selection over billions of years into the densely intertwined collaborative web of mutualism that we call life (Woolley-Barker, 2013). Organisms and environments integrate and optimize strategies to create conditions conducive to life.

Colour is one of the "environmental features" proposed by biophilic design (Kellert et al., 2008). Among the "12+ big ideas" that biomimicry has identified as potential areas for design innovation is "colours without pigments" (i.e., structural colour; Benyus, 1997). The following section analyzes traditional ways to understand and use colour and introduces the potential of structural colour for biocentered and sustainable design innovation.

2.3 Area of Focus: Structural Colour

The phenomenon of colour has been of deep interest since the times of ancient philosophers such as Aristotle and Plato. It has been studied extensively by enlightenment scientists including Galileo Galilei and Isaac Newton, and more contemporary theorists including Johann von Goethe, Johannes Itten (1970), Josef Albers (1975), and Karl Gerstner (1986).

However, a biocentered approach to colour leading to biomimetic implementation has not been clearly manifested as a prospect until the beginning of the 21st century. Peter Vukusic (2004) refers to this:

> In the 18th century Robert Hooke and Isaac Newton were among the first to explain the underlying physics of these systems [structural colour]. They correctly predicted that the iridescent colours of peacock feathers and silverfish scales resulted from their physical structure rather than pigmentation. This was a huge leap of understanding, considering that the means of seeing these structures would not be invented for a further two centuries. It was left to James Clerk Maxwell in the 19th century to develop the set of mathematical tools that now enable us to fully describe the way electromagnetic radiation interacts with matter. (p. 35)

Aristotle claimed “Nature does nothing uselessly.” With this premise in mind, a biomemetic designer observing colours in nature can come up with some very interesting initial questions:

- What is the purpose of colour in life forms?
- What strategies in nature take advantage of the ability to read colour and why?
- Why did species evolve from pigmentation to structural coloration mechanisms?
- How did they evolve from “passive” to “active” or “tunable” structural coloration?
- Why did species so diverse, with different external stimuli and from entirely different ecosystems, converge with similar structural colour mechanisms?
- Why can different structural colour results be observed within the same species?
- How can all these evolutionary features of structural colour be explained in comparative problem-solving terms?

The list of questions continues branching out in multiple directions the deeper the research on the matter becomes and as more biomimetic designers get involved. To understand the relevance of a biocentered perspective on this subject, it is necessary to integrate the multiple disciplinary realms involved, as described in previous sections of this chapter. It is also critical to create the right tools for research (i.e., the StrC Rich-Prospect Taxonomy on Structural Colour) to ignite to the design processes.

The phenomenon of colour has been a subject largely investigated from multiple angles and disciplines, offering as a result a number of studies, conventions, standards, and taxonomic classifications. Only few of these conventions follow scientific rigour; most of them rely entirely on observation limited by what human vision can perceive. Even fewer studies are dedicated to structural colour, although the scientific rigour here is essential. The following sections will briefly explore these different interpretations of the colour phenomenon.

2.3.1 Colour Theories and Interpretations

Scholars from the social sciences have demonstrated that the use of colour profoundly changes and influences the world and the way people relate to it (Young, as cited in Bille & Sørensen, 2007). In correlation with studies on colour done by Johannes Itten (1970), Karl Gerstner (1986) referred to the complexity of colour perception, proposing a five-dimensional interpretation of colour, understanding colour in terms of its relation to: (a) physics (light); (b) chemistry (substance, material, pigment); (c) physiology (sensorial organs and perception); (d) psychology (sensation in our brains after perceiving colour); and (e) mathematics (the way we measure colour according to objective parameters).

A century before the concept of phenomenology was introduced, Goethe "devised a qualitative way of seeing and understanding, that can rightly be called a phenomenology of the natural world" (Seamon, as cited in Klein, 2009, p. 12). In his phenomenological approach, Goethe moved beyond the conventional scientific study of colour in nature (Klein, 2009). Motivated by his skepticism about Newton's colour theory based on "colourless" light refracted from a prism, Goethe concluded that "colour is the reciprocity of darkness and light or, more precisely, that colour is the resolution of the tension between darkness and light" (Klein, 2009, p. 13).

Pierre Bourdieu's reflection on the agency of light and darkness (Bille & Sørensen, 2007) aligns with Goethe's approach to colour perception and the psychological and physiological dimensions of colour articulated by Gerstner (1986), in that the perception of colour is dependent on human vision and the human brain's capacity for sensorial interpretation. This approach is very useful for anthropology and the study of human cognition. The other three dimensions proposed by Gerstner, however, seem problematic from an anthropological standpoint. Bille and Sørenson criticize the scientific approach to colour (from physics, chemistry, and mathematics) as a sort of scientific determinism that denies the argument that sensorial characteristics of colour are conferred upon the human experience through [human] culture:

> It appears that a sort of "neurological determinism" has prevailed, which denies that the way people conceive and experience light and colour is also shaped in culturally specific ways. Hence, in the field of the "Anthropology of the Senses" the role of sight within different cultures has also been propelled by acknowledging that sensuous primacy, experiences and linkages between senses may vary tremendously between cultures. (Bille & Sørenson, 2007, p. 265)

Some intellectuals from science and design realms connected to material culture support this perspective, and place human perception and senses at the center of relevance (anthropocentric) when studying colour. Some others, however, leave the door open to connect mind (perception) and matter (physiology) under the same evolutionary process. Neurologist Oliver Sacks (2005) further suggests that our experiences and reactions shape our predetermined physiology. This claim is so influential to this way of thinking that Sacks (2005) also wonders: "To what extent do we shape our own brains? Does the mind run the brain or the brain the mind—or, rather, to what extent does one run the other? To what extent are we the authors, the creators, of our own experiences"? (p. 49). Colour perception in this sense can still be seen as product of evolutionary adaptation supported by biocentered science.

Juhani Pallasma (1996) links the anthropocentric interpretation of colour perception to the problems that sight capabilities create in human evolution. He addresses the importance of sight as the predominant sense, grounded in physiological, perceptual and psychological factors, playing a role in shaping our sensorial experiences (Pallasma, 2005). Pallasma claims that the dominance of the sense of sight in humans is one of the reasons for sensorial disconnection; by isolating the eye outside its natural interaction with other sense modalities, we increasingly reduce and restrict the experience of the world into the sphere of vision, “reinforcing a sense of detachment and alienation” (Pallasma, 2005, p. 39). This behaviour may be different from that of other animals, which seem to be more connected to all their senses than we are. If there’s something we can explore and learn from nature on this point, it is that all living forms are part of a multi-sensorial interconnectivity that shapes the experience of living.

In addition to more or less anthropocentric and human-centered arguments, traditional science still supports, for practical purposes, what Galileo postulated in the scientific revolution of the 17th century, in that, when studying nature (and the nature of colour), scientists should restrict themselves to studying the essential properties of material bodies. Properties like colour, sound, taste, and smell are merely subjective mental projections (Capra, 1986). This view was later supported by Newton and enlightenment scientists, and it has been useful to provide an understanding of colour as a physical phenomenon even today.

Other traditional colour theories from the arts (among them “colour-wheel models”) were influenced by Goethe’s approach to colour, and were later followed, explored, and used as the foundations of colour studies in art and design education by Johannes Itten and Josef Albers among others. Newtonian mechanistic views do not explain, for instance, relativity and quantum physics. Goethe’s phenomenological approach may or may not be seen as going in that direction. However, light has proven to be a phenomenon that aligns with Newton’s theory (supported by evidence), and advances in quantum physics knowledge have invalidated Goethe’s explanation of colour. Thus, the phenomenological discussion enters into the perception/sensation terrain, subjective to the observer.

Confronting these two ways of understanding colour (Newtonian and Goethe's propositions) is an outdated discussion in our times, and it may be like comparing the relevance of using the colour wheel (art) versus the relevance of understanding the particle-wave duality behaviour of photons (physics). Both are the results of the same reality revealed today by quantum physics, in which the only variable is the observer and the constants are yet being explored. The new challenges to the traditional colour theories, aligning either with Newton's or Goethe's, are driven by new knowledge about the physics of light. Not precisely by favouring traditional science or being against it, but by introducing a mix of perspectives, the evidential and the intangible (but still real) characteristics of colour. In this sense, traditional anthropological and material culture's perspectives on colour, such as those described by Bille's and Sørenson (2007), seem limited to providing new knowledge about colour for technological advances, for instance to understand and mimic structural colour from nature. However, more holistic and biocentered perspectives on human ecology may contribute to better understanding and implementing structural colour in the design realms, and facilitate what traditional epistemologies cannot.

2.3.2 Understanding Structural Colour

Colour observed in nature can be obtained in only two ways: by pigmentation or by structure. Pigments can be considered "active" components compared to the "passive" components of structural colour. Pigments (contained in minerals, other chemical elements, and natural or synthetic materials) get their colours when excited electrons absorb certain wavelengths of light and emit others (Hsiung et al., 2016). This energy-driven activity is absent in structural colours, which are produced by colourless surfaces and structures at a nanoscale, with details smaller than the light wavelengths producing different colours. Structural colour mechanisms produce vivid colours that last for a long time (for as long as the surface exists) in contrast to pigment colours that eventually fade under regular light conditions. With their vividly coloured exoskeletons, many old specimens in arthropod collections (e.g., in museum collections) are a testimony to the quality and durability of structural colour (Fig. 2.05).

Figure 2.05. Jamaican day-flying moths Urania sloanus (also known as the "Augustana moth"), are extinct today. The specimen in the picture was obtained for the Augustana campus of the University of Alberta in September of 2012. Vivid colours of this nearly 125-year-old specimen testify to the quality and durability of structural colours made of natural materials. (Image by Dr. Tomislav Terzin.)

Structural colour is at the crossroads of biology and physics (biophotonics)[40] and has been discussed for more than three centuries, since the first scientific descriptions offered by Hooke in 1665 and Newton in 1704 (Kinoshita, Yoshioka, & Miyazaki, 2008). However, only in recent decades and with the advancement of computing and micro and nano technologies[41] has structural colour seemed achievable as a method to produce colouration. Structural colour is described as descriptions of pigments (Benyus, 1997). It can be observed in many species as a

[40] Structural colour in physics can be described as "light interference," although a consistent scientific definition has not yet been settled upon (Kinoshita et al., 2008). The phenomenon has been recently defined as one "produced by selective light reflection from structures with periodic interfaces between materials of different refractive indices" (Hsiung et al., 2017, p. 1977), and it is often referred to in contrast to pigmentary colour or as "colour without pigments" (Benyus, 1997).
[41] Current technologies to assess and measure structural colour include refractive index matching, Transmission Electron Microscopy (TEM), and Scanning Electron Microscopy (SEM).

solution achieved by adding "information" to material surfaces at the nano-scale. Structural colour can be understood as various physical effects of the interactions (e.g., interference or scattering) between light and the body surface. It can be defined as "variations of light scattering at the interfaces of objects that differ in refractive index" (Prum & Torres, 2003, p. 2409), where the incident light bounces back from the "nano-structured" surface in the form of different hues.

It is important to make a distinction between structural colour produced by the coherent versus incoherent scattering of light. In incoherent scattering, colour is a function of the properties of individual scatterers (e.g., water molecules in blueish ice and snow, or oxygen in a blue sky), whereas in coherent scattering colour is determined by the spatial distribution of light-scattering interfaces (Parker, 1998), such as skin, cuticles, feathers, scales, etc. in life forms. The biomimetic interest in structural colour focuses on the latter; however "quasi-coherent" structures have also been observed as variations of diffraction grating mechanisms that produce vivid non-iridescent colours in a variety of avian species and arthropods (Seago, Brady, Vigneron, & Schultz, 2009).

Coherently scattered structural colour is abundant among life forms, present in a wide range across natural kingdoms, and observed in: Animalia (Parker, 1998; Prum & Torres, 2003, 2004; Saranathan et al., 2015; Seago et al., 2009; Vukusic, 2004); Plantae (Jacobs et al., 2016; Vignolini et al., 2012); and Fungi and Bacteria (Hsiung, Justyn, Blackledge, & Shawkey, 2017; Starkey & Vukusic, 2013). Abundant cases of structural colour in birds, fish, and arthropods have been studied for many decades, yet many new aspects or variations of what science knows about structural colour are waiting to be discovered (Saranathan et al., 2015; Vukusic, 2004). Arthropods in particular (beetles, butterflies, spiders, flies, etc.) offer a vast and diverse number of mechanisms to produce structural colour (Saranathan et al., 2015). A commonly accepted classification of structural colour in biophotonics determines three different kinds of nanostructures: one-dimensional (1D), two-dimensional (2D), and three-dimensional (3D; Vukusic, 2004). These structures can cause different kinds of light interference and scattering: (a) surface diffraction gratings, (b) single or multiple thin-layer reflection, or (c) photonic crystals (Parker, 1998; Vukusic, 2004).

Mammal species (in a comparative much smaller number though) also present structural colour, such as the blue skin of some species of primates and marsupials (Prum & Torres, 2004). Other curious cases of structural colour among mammals are the white colour—although produced by incoherent scattering—we see bouncing back from polar bears' hair (polar bears are black-skinned and hairs are transparent) or the blue bouncing back from the iris of a human eye; there are no blue pigments in blue eyes, or in green eyes, which are a mix of "structural blue" and the dark-yellowish pigmentation of melanin.

A biocentered approach to colour (and structural colour in particular) means placing "life genius" (Benyus, 1997) at the center of design strategies to work with colour. Scientists studying structural colour in life forms consistently agree that colouration is a product of evolutionary adaptation (Parker, 1998; Prum & Torres, 2003, 2004; Saranathan et al., 2015; Starkey & Vukusic, 2013), with colour functionalities connecting behaviour and communication intra and interspecies (e.g., mating, aposematism, crypsis, etc.). Charles Darwin, in 1859, anticipated this characteristic of evolution when he observed that, "whenever colour has been modified for some special purpose, this has been, as far as we can judge, either for direct or indirect protection, or as an attraction between sexes" (as cited in Parker, 1998, p. 2345).

The premise *form follows function*, so appealing to designers, is observed in nature, too; the purpose of such sophisticated colour uses through nano-structural "designs," adapted after an evolutionary process of optimization, is at the core of life's "methodology." Based on the phylogenetic distribution of structural colour in birds, for instance, mechanisms of colour production have evolved convergently more than 50 independent times within existing species of birds (Prum & Torres, 2003). Learning how these "designs" work, understanding why, where, and what for, can lead to powerful ideas for sustainable innovation in colour in a variety of areas, including: optics, the energy industry, paints, textiles, electronic displays, photovoltaic films, lenses, and construction materials (Saito et al., 2011; Saranathan et al., 2015; Vukusic, 2004; Xiao et al., 2015).

The understanding of colour mechanisms in nature, with the help of modern microscopic, digital, nano, and quantum technologies, allows scientists and designers to access information that half a century ago was speculative terrain. Still far from completely understood and mostly unexplored (based on the number of species studied versus the potential millions yet to be discovered), the prospect of learning from nature how colour can be produced sustainably has changed the minds of scientists and designers alike, raising it to a new foundational philosophical level.

2.3.3 Applications and Implications

Colour production in the design industry has focused on two opposed but fundamentally detrimental processes consistent with the anthropocentric perspective of material production and technologies in the 20th century:

1. Subtractive mixing by pigmentation, based on mineral extraction, chemical (and often toxic) compounds, and high energy-consuming processes for colour transfer and fixation. These ways of producing colour have been highly contaminating, wasteful, and inefficient. While high-tech industries have focused on colour accuracy and

standardization (e.g., Pantone®[42] swatches or CMYK[43] printing systems), the results of applied colours in printing materials are at times unpredictable, and it is impossible to achieve 100% of accuracy in reproducing, for instance, colour photography. In addition, and following the second law of thermodynamics, printed pigmentary colours are entropically unstable overtime (pigments decay and fade away naturally under normal light conditions).

2. Additive mixing by light beams or bits, observed in electronic displays, is based on phosphorescent materials and exotic minerals, such as tungsten, gold, and mercury. These materials are also highly wasteful and contaminating, especially considering the massive number of electronics produced globally, and the electronic waste generated by the rapid obsolescence of devices such as smartphones, TV sets, and computers.

In contrast to these problematic and unsustainable ways of producing colour, nature offers us a lesson from the ways it produces colour. Living creatures evolved from billions of years of "processing information" on what works and what doesn't to achieve colour (either using pigment or not) in ways that were frugal, efficient, and effective. It is thought that the Cambrian explosion 500 million years ago triggered the evolution of colour production among species, when the manipulation of light began to influence the survival of many animals (Vukusic, 2004). According to this hypothesis, "Nature learned relatively early about the way light interacts with periodic structures due to the evolutionary selection advantages it offers" (Vukusic, 2004, p. 35).

An estimated 8.7 million species live on earth.[44] When achieving colour, they do so in a

[42] Pantone is a system for matching colours that became the standard for printing, design and advertising industries.
[43] CMYK (cyan, magenta, yellow, and black) refers to the four inks used in process (mix) colour printing (i.e., inks, inkjet, and laser toner).
[44] UNEP's World Conservation Monitoring Centre (UNEP-WCMC), in Cambridge, UK. See: http://www.coml.org

sustainable fashion with 100% biodegradable or recyclable materials, low energy input (usually sunlight), and abundant and simple materials that are locally obtained, grown, and created by combining a small subset of natural elements from the periodic table.[45] All this is done under regular ambient conditions. Such a "primitive" way of colouring is one of the highest lessons of sophistication and "intel" we can learn from nature.

Structural colour is among the most promising areas to explore in nature to inform and inspire sustainable design solutions. It is also one of the most promising areas for innovation within the biomimetic design arena (Caro, Stoddard, & Stuart-Fox, 2017; Hsiung et al., 2017; Kennedy et al., 2015; Kinoshita et al., 2008; Saito et al., 2011; Xiao et al., 2015), attracting design innovation ideas constantly (Kennedy et al., 2015; Kinoshita & Yoshioka, 2005), and establishing an area of innovation that may grow in the coming years, with more case-studies, concepts, prototypes, and commercialized solutions. Structural colour implementation may play a crucial role within the prospect of new and sustainable technological advances, for instance in screen display technologies, printing and colouring industries, signaling and communications, and photonic computing,[46] among other areas. However, it is challenging to artificially mimic these complex structural colour mechanisms in order to achieve a method for fabrication. These mechanisms can be mimicked with current nanotechnologies (Zhang & Cheng, 2015), additive manufacturing (Boyle, French, Pearson, McCarthy, & Miyake, 2017), and other digital ways of fabrication (Colusso et al., 2017), but these techniques are not fully developed yet and they are still evolving; therefore, structural colour has been only applied in a few initial products and

[45] The periodic table of elements is a tabular display with the chemical elements ordered by their atomic number.
[46] Current research on a new generation of transistors will make it possible to use photons instead of (or combined with) electrons to produce photonic devices that are 100 times faster than electronic devices. This can revolutionize computing science and create new opportunities to explore quantum computing. See: http://www.sciencealert.com/scientists-have-figured-out-how-to-switch-between-electrons-and-photons-in-a-single-transistor

prototypes in the last 10 years (as mentioned in Chapter 1, Fig. 1.01). There is still much to learn from nature, and some limitations to tackle in order to successfully benefit from structural colour.

One of the challenges of producing structural colour is that there is a limited capacity to achieve stable hues independently of the angle of incidence of a light source. When hues are unstable, we perceive colours with iridescence and metallic effects. These effects may not be suitable for many colour applications, such as replacing traditional paint, inks, and dyes. However, recent scientific discoveries about structural colour have led to new possibilities for developing further technologies, some of which can avoid or control iridescence (Hsiung et al., 2017; Saito et al., 2011; Saranathan et al., 2015; Starkey & Vukusic, 2013; Xiao et al., 2015).

2.4 Conclusion

This review summarized the elements, theories, and perspectives that informed this research. It served as an analytical framework to understand the epistemological background, philosophical perspectives, and areas of study connected. These areas were organized in three sections: the epistemological foundations from design, material culture, and human ecology; the philosophical foundations from sustainability, anthropocentrism, biocentrism, and biocentered design; and the area of interest and case study, structural colour.

The arguments addressed in this review to support the epistemological foundations come from pieces of literature written by key intellectuals in design, material culture, and human ecology. These intellectual include Maldonado (1972), Buchanan (1992), Fry (2005), Rittel and Webber (1973), Papanek (1984), Miller (2008), Prown (1982), Hodder (1994), Ingold (2007), Tilley (2007), Knappett (2005, 2007), Latour (2005, 2014), Bennett (2004, 2010), and Moran (2010). See Fig. 2.06.

Figure 2.06. Key intellectuals from design, material culture, and human ecology.

The philosophical foundations are shaped by significant theories on and propositions for the areas of sustainability, anthropocentrism, and biocentrism, reflected in a comprehensive list of influential authors: Lovelock (1987), Bejan and Zane (2012), Varela et al. (1974), Jantsch (1980), Mandelbrot (1967), Capra (1982, 1996, 2010), Gibson (1977), E.O. Wilson (1984), Steiner (1995), Kellert et al. (2008), Crutzen (2006), Benyus (1997), Wahl (2016), Strauss (1990), Westney et al. (1988), Visvader (1986), McIntosh (2012), Orr (2002), Bateson (1972), Guba (1990), Nielsen (1990), Kuhn (1996), Crilly (2010), Koestler (1967), Hawken (2014), Naess (1973), Sterba (2011), Taylor (1983, 1986, 2008), Kant (1999), Leopold (1970), Spinoza (in Watson, 1983), Vogel (2003), and Spitler (1982). See Fig. 2.07.

Figure 2.07. Key intellectuals in the areas of sustainability, anthropocentrism, and biocentrism.

The area of focus of this study, structural colour, is contextualized by seminal theorists in colour and sensory studies, from Aristotle and Plato (in Watson, 1983), to Galileo, Newton, and

Maxwell (in Vukusic, 2004), and more contemporarily from Goethe (in Klein, 2009), Itten (1970), Albers (1975), Gerstner (1986), Bille and Sørensen (2007), Sacks (2005), and Pallasma (2005). Structural colour in particular is addressed using the most relevant scientific literature on the matter, from authors such as: Prum and Torres (2003), Parker (1998), Vukusic (2004), Starkey (2013), Kinoshita et al. (2008), Seago et al. (2009), Saranathan et al. (2015), Vignolini et al. (2012), and Hsiung et al. (2016); see Fig. 2.08. These authors have made the utmost contributions to knowledge in the area of research of structural colour, and embody the most reliable source of knowledge on structural colour available for biocentered design innovation.

Figure 2.08. Key authors on colour studies and structural colour sciences.

Based on the epistemological and philosophical foundations, and the area of focus described in this literature review, the following list of conclusions summarizes the nature and purpose of this research project:

1. Designers are critical thinkers, and trained to be problem identifiers, generalists, and reflective practitioners, conscious of a field highly contextualized in a wicked problem environment.
2. Material culture methodologies can make an important contribution to the transition from anthropocentric design to biocentered design.

3. An anthropocentric standpoint places humans at the center of relevance and material products and artifacts as an expression of human culture. The concept of materiality can be seen as an anthropocentric construction, a convention to understand and communicate what humans experience and perceive. From a structuralist standpoint, material culture considers nature as opposed to culture (i.e., Pierre Bourdieu, Peter Wesbroek).
4. A biocentered standpoint places nature and life at the center of relevance and humans as a non-exclusive part of it. From a posthumanist standpoint (i.e., Ingold, Moran, Gibson, E.O. Wilson, Capra) nature and culture are not only *not* opposed but intrinsically entangled.
5. Radical Human Ecology (McIntosh, 2012) is a human ecologist biocentered approach. This approach offers the potential to connect human ecology and design, and design to science at the biomimicry playground.
6. The idea of generalism (Papanek, 1984; Strauss, 1990) is a transcendental characteristic that connects a human-centered discipline like human ecology and a biocentered discipline like biomimicry; and it contrasts with the idea of overspecialization (Koestler, 1967; Moran, 2010).
7. Emerging disciplines, such as biomimicry, and transforming disciplines, such as human ecology, are part of a transition situated at a shifting point of the dominant design paradigm (Kuhn, 1996; Wahl, 2016). The synergies and commonalities between human ecology, design disciplines, and biomimicry, help to create the conditions for an evolutionary path from an anthropocentric to a biocentered ethos.

8. In contrast to anthropocentrism, biocentrism can be seen as an ethical point of view that extends inherent value to all living things, not only humans, in order to contribute to sustainable futures.
9. Sustainability from an anthropocentric–business-as-usual approach favours short-term innovation while from a regenerative–biocentered approach (Wahl, 2016), sustainable innovation helps the transition to long-term effective solutions.
10. The way colour is produced in products and the built environment belongs to an unsustainable paradigm represented by anthropocentrism.
11. Mimicking structural colour from nature is the most sustainable way to develop new technologies and methods to produce colour; it avoids toxic waste and reduces energy consumption while increasing the quality and lifespan of colouration.
12. There is still much to learn from nature, and some limitations to tackle in order to successfully benefit from structural colour. New findings on the science of structural colour are promising for design innovation, and invite scientists and designers to build more bridges to connect science knowledge with design for biomimetic innovation.

CHAPTER 3: METHODOLOGY—MULTIDIMENSIONAL APPROACH AND MULTIPLE METHOD STRATEGY

3.1. Multidimensional Approach

Qualitative research methodologies and methods are often anthropocentrically focused and can take various forms of approach for studying the artifacts of design. A comprehensive introduction to anthropocentrism and biocentered thinking was offered in the literature review of this dissertation. This methodology chapter provides an overview of several approaches to conduct research in this given context. This chapter explores in particular what a multidimensional, multidisciplinary approach and a multiple-method strategy offer to biocentered design research. It explains the methods, concepts, and strategies chosen for the study, and how these can work together for the purpose of this research project. Methodological thinking at the early stages of the project fostered strategic decisions on choosing particular "approaches" and "ways" that were beneficial in addressing the research question and subsequent questions. One intent of this chapter is to define the roles of those "approaches" and "ways." The other intentions are to integrate and emphasize synergies between the different perspectives analyzed, and the methods, concepts, and strategies chosen.

A multidimensional approach to research requires a previous analysis of the diverse methodological approaches that are inherent to the subjects investigated and are shaped by the different background epistemologies present in this work: (a) a design methodological approach, (b) human ecology and material culture methodological approaches, and (c) a biomimetic science-oriented methodological approach. What follows is a synthesis of these three differentiated approaches.

3.1.1 Methodological Approach Shaped by Design: Practice-Based, Generalist, and Wicked Problem-Oriented Disciplinary Characteristics

Design has been increasingly accepted as a discipline on its own terms of inquiry and, in the process, it has been differentiated from other disciplines (Bonsiepe, 2007). Yet, design eludes reductionisms and remains a pragmatic and flexible activity (Buchanan, 1992) whose approaches can be diverse and complex, and can demand designers to think as generalists and work as synthesists (Papanek, 1998). Generally speaking, if we can place all design disciplines under one big disciplinary umbrella, we may possibly agree that the design methodology that results, and the research methods practiced, differ from traditional scientific and social sciences methods in the “things to know,” the “ways of knowing,” and the “ways of finding out” (Cross, 2013). Design methodology, and its methods practised, can be more adventurous, innovative, and unconventional than scientific and social sciences methods. Methods practised by designers often involve risks of bypassing disciplinary boundaries. Also, because of the ways in which they are executed, these methods are often considered less serious by other non-design researchers. Examples of this are observed in qualitative ethnographic design studies, such as co-design and participatory design activities.

In such studies, participants are levelled up to professional practitioners in order to co-create design work, conscious that there is a big difference in training and skills between the professionals and the amateur or casual design practitioners. The material results of these experiences may often look unprofessional, subjective, and far from real design work. However, researchers can detect important patterns that may help them to develop better ways to understand what the final users of design need. What counts is the process over the material results. Design methods tend to be practice-based, a characteristic of advanced design research.

The effectiveness of these methods depends on their capacity to bridge theory and practice (Frascara, Meurer, van Toorn, & Winkler, 1997). There is a distinction in design research between the research that is done to develop a design project and design that is done to understand designerly ways (Cross, 1982) of knowing and doing (not necessarily a design project); thus, it is useful here to disentangle the act of "designing" and the act of doing "design research" as ways to define this project's methodological approach. While both concepts connect to "design thinking," the part of this project that involves designing is the development of the academic prototype itself (the StrC ecosystem), whereas the parts that involve researching are the methods applied for collecting and analyzing the data obtained by using the prototype.

The choice of the right methods from a design perspective may seem inappropriate from a scientific perspective, but still effective for the design research task that can eventually also be translated into more traditional quantitative and qualitative scientific research. The multiplicity of methods (both qualitative and quantitative) as well as interdisciplinary strategies (to advance knowledge and to address design problems) are not uncommon either in design practice or design research. The way design connects to multiple methods and disciplines is by applying the Aristotelian concept of *praxis.* Aristotle defined praxis as "the relation between thinking and things" (Crouch & Pierce, 2012, pp. 39–40). Praxis bridges reflection and reflexivity in the design process, and allows designers to be *reflective* practitioners (Crouch & Pierce, 2012; Papanek, 1984; Schön, 1983; Strauss, 1990; Strickfaden et al., 2015). Despite the diversity of methods within design methodology, which differentiates design from other disciplinary realms, there is one general condition that remains common to design practices and it may connect to other scientific methods of research: all design problems seem to fall under the *wicked* *problems*[47] category, in which "design problems are 'indeterminate' and 'wicked' because design has no special subject matter of its own apart from what a designer conceives it to be" (Buchanan, 1992, p. 16). From this angle, design can be associated with or disassociated from different methodological perspectives without losing the essence of the design epistemology. For instance, some authors claim that one of the reasons for distinguishing design from science is that design problems are ill-defined, ill-structured, or *wicked*, whereas science problems are mere "puzzles"—or *tame* problems—to be solved by applying well-known rules (Buchanan, 1992; Cross, as cited in Farrell & Hooker, 2013). Other authors point to the opposite perspective, that both design and science have common core cognitive processes, and the kind of problems both realms face can be considered *wicked* problems. Farrell and Hooker (2013) argue that:

> [a] design method, like [a] scientific research method, is a product of a common core cognitive process and management of pragmatic complicating conditions, and that methodological procedures and skills break into ways of progressing each of core and pragmatics and managing their interactions. This structure can be exploited—for instance, by transfer of problem-solving experiences and strategies, whether across subdomains within design or between science and design, despite pragmatic differences. (p. 701)

Thus, "rather than dividing design from science cognitively, the distinction helps unite them" (Farrell & Hooker, 2013, p. 683). It is the intention of this research to bridge design methodology with science methodology, and to deliberately emphasize the differences between realms.

3.1.2 Methodological Approach Shaped by Human Ecology and Material Culture: More Holistic and Integrative Characteristics

Human ecology and material culture studies are two influential epistemological domains that have shaped this research program. They not only serve as a space for hosting the involved

[47] Wicked Problems were introduced in Chapter 2: they are a kind of problem that is difficult or nearly impossible to solve completely, because of incomplete, contradictory, and changing requirements that are often difficult to recognize. All design problems can be in a sense potential wicked problems, from which ill-formulated solutions can lead to more and higher level problems.

areas of expertise (design, sustainability, biomimicry) and areas of personal interest (biocentered design and structural colour), but also as synergistic agents of this doctoral investigation, which will result in a human ecology, material culture, and design studies degree. In the first domain, human ecology, exploring multiple areas seems a natural practice (McIntosh, 2012). This connects well to the intention of a multidimensional approach and serves as a multidisciplinary space that benefits this overall research process. Human ecology has an integrative scholarship capacity (D. Steiner, 1995), and offers the space for diverse perspectives—usually fragmented—to arrive at a common ground of understanding. Dieter Steiner (1995) proposes four dimensions of integration in human ecology: the transdisciplinary, the transcientific, the evolutionary, and the transpersonal. Implicit in all of these dimensions is the transformative character of human ecology. This character, if truly and thoughtfully applied, aligns with the other epistemologies of this project's research interest. With design epistemologies in particular, human ecology shares the characteristic of being an interdisciplinary field that tends to push or remove disciplinary boundaries. Similar to design, when such new spaces are created, agency, innovation, change, and transformation happen as a natural step. Human ecology also presents commonalities with what a biocentered perspective proposes (as highlighted in the Chapter 2 literature review), and this facilitates a multidimensional approach that organizes methods under one common methodological process.

The second domain, material culture, may present some additional complexity to conciliate a common methodological ground oriented to biocentered thinking (as was also remarked in the literature review). On one hand, in tune with design research and practice, material culture is seen as an interdisciplinary field too, and in tune with human ecology it can also be an integrative discipline (Moran, 2010). Following this logic, material culturists may align with the roles of generalists and reflective practitioners (Papanek, 1984; Schön, 1983;

Strauss, 1990). On the other hand, in the fundamental definitions of *culture* and *material* there is a division. On one side are those in favour of a more integrative (and prospectively biocentered) perspective (e.g., D. Steiner, Jantsch, Nielsen, Ingold) the ideas of which are aligned, for instance, with E.O. Wilson's Theory of Biophilia (Wilson, 1984), Gibson's Theory of Affordances (Gibson, 1977), and Wahl's idea of regenerative cultures (Wahl, 2016). On the other side are those with a more anthropocentric perspective (e.g., Prown, Fleming, Bourdieu, among others), who tend to attribute culture only to humans or consider it an exclusively human domain, and tend to consider nature predominantly as a human–social construction. These Cartesian divisions, separating humans and culture from nature, suggest that the interpretation of materiality needs to be studied beyond the evidence-based scientific paradigm. There is a risk, though, in challenging such anthropocentrically rooted views in material culture. If the biocentered argument is not clearly stated and supported by a robust theoretical frame, the discussion can lead to a misinterpretation of biocentered thinking, as one more humanist view "under a different guise." Perhaps it is more accurate to conceptualize biocentered thinking as a post-humanist standpoint, with post-humanism being part of material culture studies. In any case, the research methods explored by material culture researchers, beyond their anthropocentric characteristics, are of great value for a multidimensional methodological approach.

3.1.3 Methodological Approach Shaped by a Biomimetic Scientific-Design Oriented Epistemology

The emerging discipline of biomimicry proposes a methodology based on Life Principles,[48] which is essentially a design methodology. At the core of this design methodology

[48] The Biomimicry Institute has promoted a biomimicry methodology for almost two decades, based on the "Life Principles" model (Baumeister, 2014; Benyus, 1997). In recent years this methodology has been increasingly accepted, validated, and applied in design, engineering, and technology realms (Helfman Cohen & Reich, 2017; Wahl, 2016).

is interdisciplinarity and the transfer of knowledge between design and science domains (Helfman Cohen & Reich, 2017). Life Principles methodology is intended to assist the design process and to address design problems by bringing innovative alternatives inspired by evolutionary strategies found in nature. The transfer of knowledge between science and design, implicit in biomimetic practices, creates a common understanding and a shared perspective, if not completely at the methodological level, at least at a conceptual level. It is the high interest in exploring and discovery for the sake of innovation and new knowledge that brings scientists and designers to a common conversation and a common terrain. In other words, biomimicry sets the stage to facilitate the integration of design and science, while continuing to adopt the traditional scientific method based on rigorous seeking of evidence, peer reviewing, and skeptic inquiry as crucial components that must remain at the core of the biomimicry methodology.

Comparatively, the scientific transfer of knowledge from methods used in biological sciences to the field of design is more rigorous than the services that design brings to scientific methods, in terms of the influence that one domain has over the other (Helfman Cohen & Reich, 2017; Sartori, Pal, & Chakrabarti, 2010). A design requirement or challenge may not influence the way the rigorous scientific method is conducted to provide information to the design process, however the scientific method may certainly influence the way the design process evolves towards innovative solutions.

This biomimetic scientific-oriented epistemology influences the way methods and tools have been chosen to conduct this research. For instance, the use of an academic prototyping case in the form of a rich-prospect browsing interface uses a metaphor inspired by taxonomic classification (de Hoog, 1981; Simpson, 1961) and phylogenetic modelling proposed by systematics studies from biological sciences (Baum & Smith, 2013). As in the biomimicry methodology, biological sciences informs the design process. The biomimicry methodology proposes two ways of approaching this process: the “challenge to biology” and “biology to design” (Baumeister, 2014; Fig. 3.01). The first approach proposes to find working solutions in nature for a given human problem, and the second proposes identifying human problems that could be solved by mimicking solutions already studied or being studied in nature. The StrC is an example of the second approach.

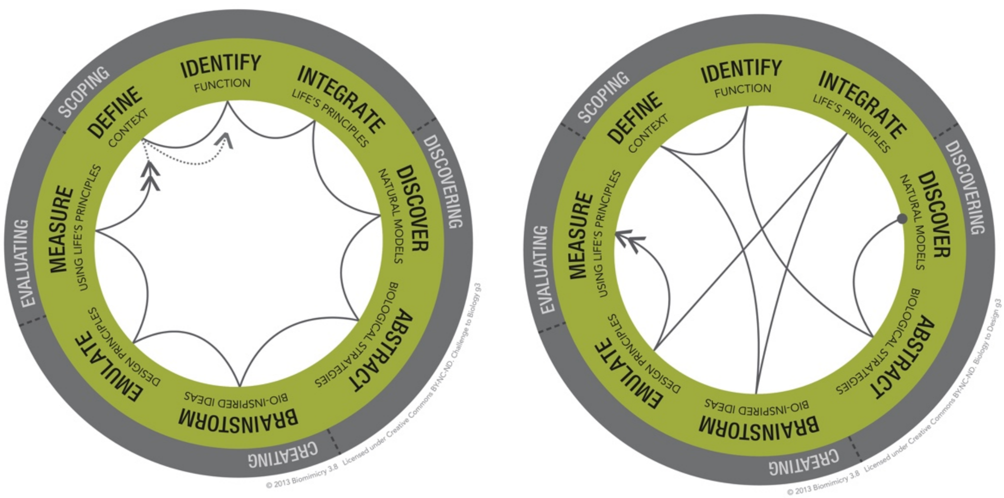

Figure 3.01. Two approaches proposed by the biomimicry methodology for the design process. The StrC is a tool for research inspired by the “biology to design” approach from the biomimicry methodology.

Scientific input greatly influences the ideation stages of interfaces like the StrC and may shape the outcomes of the design process. Additionally, inspired by the concept of self-organizing systems or *autopoiesis*,[49] the academic prototyping tools of this research may evolve as they become informed by the process of researching and self-organizing their functions during the development, testing, and use stages.

[49] As introduced in Chapter 2, autopoiesis is a term coined by scientists Maturana and Varela in the early 1960s and recurrently mentioned by Material Culture scholars (Ingold, 2007; Jantsch, 1980). Autopoiesis is a theory that claims that living systems are “self-organized” mechanisms that maintain their particular form despite material inflow and outflow, through self-regulation and self-reference. This is often linked to the principles of resilience, the second law of thermodynamics, and attuned with the life principles proposed by biomimicry methodology.

A multidimensional approach implies aligning methodologies in a more holistic and integrative way, finding commonalities and opportunities that may lead to decisions on methods and strategies for addressing a common research goal. A multidimensional approach can be seen as a “tool kit” of multiple methods, concepts, and strategies. These methods, concepts, and strategies are not limited to a design approach, a material culture approach, a human ecology approach, or a biomimetic approach. Rather, they take from all these disciplinary realms the most relevant possibilities for the benefit of the project. Such methods should follow research standards given by: (a) a worthy topic, (b) rich rigour, (c) sincerity, (d) credibility, (e) resonance, (f) significant contribution, (g) ethics, and (h) meaningful coherence (Tracy, 2010). A multidimensional approach also has a transformative effect on disciplinary fragmentation and divisions, particularly when it comes to filling the gaps that are sometimes common in confronting approaches such as anthropocentrism and biocentrism.

A multidimensional approach opens the space for a multiple methods approach, capitalizing on the rich diversity of concepts, techniques, strategies, and research tools available in a multidisciplinary research environment. This research can be seen as predominantly qualitative, with methodological elements taken from ethnographic research (i.e., semi-structured interviews), and hermeneutics (i.e., visualized content-text analysis), and with quantitative causal-comparative components (i.e., a structured survey). Yet from a methodological perspective, any strict classification of the methods could deviate this project’s exploratory nature.

The quantitative tools are intended to quantify the data collected, generalize the results, and measure the incidence of the views from the participants of the study. The qualitative components followed the quantitative, to further explore and gain understanding of underlying reasons not fully detected in the quantitative data, and to collect insights, generate hypotheses, and reveal dominant trends across views.

A multidimensional approach and multiple methods research provided a framework for the study, determining the scope, organization, and distribution of the participants; and using triangulation techniques (Denzin, 1970) to process multiple perspectives and diverse sources of data. The outcomes of this framework opened a space for dialog between disciplines, to analyze existing theories, and to discuss new angles and propositions on the subject of structural colour and its understanding and biomimetic implementation.

The exploratory aspect of this approach aligns also with the concept of doing "research in the wild" (Callon & Rabeharisoa, 2003), a new terrain that creates forms of collaborative research where mutual enrichment prevails in guiding the actions of those conducting research and those participating and contributing to it. New forms of collaborative research can create "trading zones" (Callon & Rabeharisoa, 2003) where the circulation of data is relevant and beneficial for all the parts involved in the study.[50] This situation has been observed in preliminary phases of the StrC work, which involved researchers and students participating from different disciplines (biological sciences, computing sciences, physics) in the development of the necessary elements to build a first working prototype for study purposes. Research trading zones were created as a result of these synergies from which the different actors obtained benefits for their own research purposes, which then resulted in all of the involved parts being directly concerned with the knowledge produced. In an interesting way, the participation of contributors to the StrC made it a project of use to the research of the different actors. In "research in the wild" terms, all parts were objects and subjects of the contributors' research (Callon &

[50] There is a parallelism with the "riparian zones" in biology and the "ecotones" in biomimicry, where "the action" of adaptation, negotiation and exchange happens, at the verge of an ecosystem.

Rabeharisoa, 2003). It is hoped that these collective dynamics will extend the lifespan of the StrC as a research ecosystem in the long term.

3.2 Precedent-Based Design in Biomimicry

The concept of precedent-based design (PBD; Oxman, 1996) proposes addressing new design problems by assessing design solutions that already exist in the market (design precedents). PBD allows designers to analyze and interpret design problems, particularly at the initial stage of the process, helping designers to establish and develop their ideas into more innovative solutions. Identifying and observing precedents as part of design research may prevent ill-formulated processes that try to "re-invent the wheel," which in turn may benefit the designers, and ultimately the end user of the design (Strickfaden, Fiorentino, Martin, Fast, & Eales, 2018).

There is a strong analogy of mechanisms between the PBD proposition and biomimicry principles and methodology, in that both are based on previous cases on record, and both promote design processes founded in precedent cases to solve new problems and avoid unnecessary risks of failure. PBD assesses design solutions already available in the market by considering what other designers have done, successfully or unsuccessfully, to address determined design problems. Biomimicry seeks "design solutions" already available in nature. It is driven by the understanding of nature as "mentor, model, and measure" (Benyus, 1997) of all design innovations, and facilitates implementation through the Life's Principles methodology. However, unlike biomimicry, PBD does not mimic the precedent designs studied. PBD proposes that the more extensive the collection of precedent cases is, the richer the design process and results can be. This is also consistent with the biomimicry approach. Applying PBD usually requires the construction of a library with diverse and abundant design precedents (Oxman, 1996). The same line of reasoning is observed in biomimicry, which studies the most complex and extended "collection of known precedents"—the result of billions of years of "research and development" (Benyus, 1997). In PBD, looking at design precedents may inspire the design process in a different direction, triggered by sources that have been previously researched (Strickfaden et al., 2015). Browsing previous related designs as organized memories can inspire designers' innovations when facing new challenges (Oxman, 1996; Oxman & Oxman, 1993). In biomimicry, looking at precedents in nature can trigger innovation in new directions. Nature-evolved solutions (form, function, strategies, and mechanisms) have inspired new technologies, materials, and whole-system-thinking design solutions for many years.

The collections included in the StrC and available through a rich-prospect browsing experience reinforce the PBD-biomimicry analogy. The StrC database consists of collections of precedent-based "designs" from nature, available to solve new challenges involving the production of colour by biomimetic design. Similar to PBD collections, the more comprehensive and large in size the StrC database can become, the more opportunities it can offer for design innovation.

3.3 Academic Prototyping Concept

Although the concept of seeing "prototypes as theories" was suggested in preliminary digital humanities research work (Galey & Ruecker, 2010; Ruecker, Brown, et al., 2009; Ruecker, Radzikowaska, et al., 2011), the concept of academic prototyping was formally introduced as a research method[51] by Ruecker, Adelaar, et al. (2014) when they presented "The

[51] After an exhaustive investigation of different literature search engines—Scopus, LISA: Library and Information Science Abstracts, Inspec, Web of Science, EBSCO Discovery, Academic Search Complete, Google Scholar—and with the assistance of Angie Mandeville, the UofA Librarian designated for Human Ecology, evidence of any use of the term "Academic Prototyping" as a research method could not be found prior to 2014. Generally, the term refers to generic ways to describe any prototyping process in academic areas (particularly in engineering, computing, and

Case of the Dynamic Table of Contexts," a rich-prospect browsing (see Section 3.4) and experimental interface prototype case. Academic prototyping is a way of producing new knowledge about specific ideas through the design of an experimental prototype (such as a digital interface). The goal is not just the production of such a prototype, but rather experiencing prototyping as a phase in a critical process (Ruecker, Adelaar, et al., 2014). Academic prototyping puts traditional understanding of design processes under scrutiny. It challenges fundamental assumptions on the relationship of tools of interpretation (i.e., hermeneutics), research products, and research processes. In addition, it suggests that design can become a process of critical inquiry itself, rather than just the embodiment of its results (Galey & Ruecker, 2010).

The difference between *prototyping* and *prototype* is more than grammatical, and can be compared to semantic differences between *computer* and *computing*, or *model* and *modelling* (Galey & Ruecker, 2010). Thus, it is necessary to make a distinction between academic prototyp*ing* and academic prototyp*es,* to understand the purpose of using the term for this project; while the first refers to this pioneering research concept, the second only refers to the products of the process of making something, also defined as samples, models, or mockups. To sum up, other ways of prototyping in academia (e.g., rapid prototyping) may not be related to this research method idea.

Over a number of years, yet before the term "academic prototyping" was used in the sense that Ruecker et al. proposed, I was involved in the design and development of several digital tools and interfaces that could fit under the academic prototyping definition. These tools

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sciences) but not a research method. This confers originality to Academic Prototyping. New uses of it as a method may be discovered along with this and other future projects.

were developed as hermeneutic exercises (Hodder, 1994), the visual results of which showed an underlying process of exchanging information and knowledge (Ruecker et al., 2011). Such tools offered not only the possibility of developing a final working tool and the dissemination of findings, but also the opportunity to learn about specific aspects and nuances while researchers were creating them. The design and development of a research tool, usually aimed to achieve a final version, in this case turns out to be a more important concept that just the predictable outcomes. The design and development stage became “the research tool” itself, in a heuristic (Helfman Cohen & Reich, 2017) and stochastic (Jantsch, 1980) manner, welcoming the unexpected, independent of how many working versions (if any) were achieved. Prototyping in this sense “can become a pedagogical tool to promote spaces of doubt and care,” in a kind of “cosmopolitan encounter” (Hermansen & Tironi, 2018 p. 224), and it can challenge the dogmatism of user-centered design (Hermansen & Tironi, 2018). Consequently, applying academic prototyping as a method is a central aspect to this research project, and influences the way the studies were planned and conducted.

The design and implementation of the StrC ecosystem has the potential to become a fully functional rich-prospect browsing research tool, but also the potential to reveal important research outcomes from the process of creating and using the ecosystem as an academic prototyping interface.

3.4 Rich-Prospect Browsing as a Tool for Research

Rich-prospect browsing (Ruecker, 2003) is an ethnographic form of inquiry manifested in a visual digital environment (Giacometti, 2009; Ruecker et al., 2011). A rich-prospect browser can be described as an experimental interface similar to a website, in which the home page displays a visual representation of every item in a given collection, combined with tools for manipulating the display (Fig. 3.02). Such an interface can be categorized as an experimental prototype, and the analysis of it can rest on how effective the tool is in providing an "affordance" (Gibson, 1977) for the user to carry out a given research task (Ruecker et al., 2011). Complementary tools included in this interface are usually dynamic visualizations resulting from grouping and regrouping taxonomic information found in a predetermined database. The whole rich-prospect browsing ecosystem (the main home page and additional constituent tools) may help the user not only to reach the desired data with more accuracy or in less time, but also to find patterns and reveal other angles of the information collected by extending the possibilities for reading the results in different ways.

A rich-prospect browsing interface is a suitable match for academic prototyping. Both, in fact, can be paired not just as two concepts, but as one synergetic binomial method.

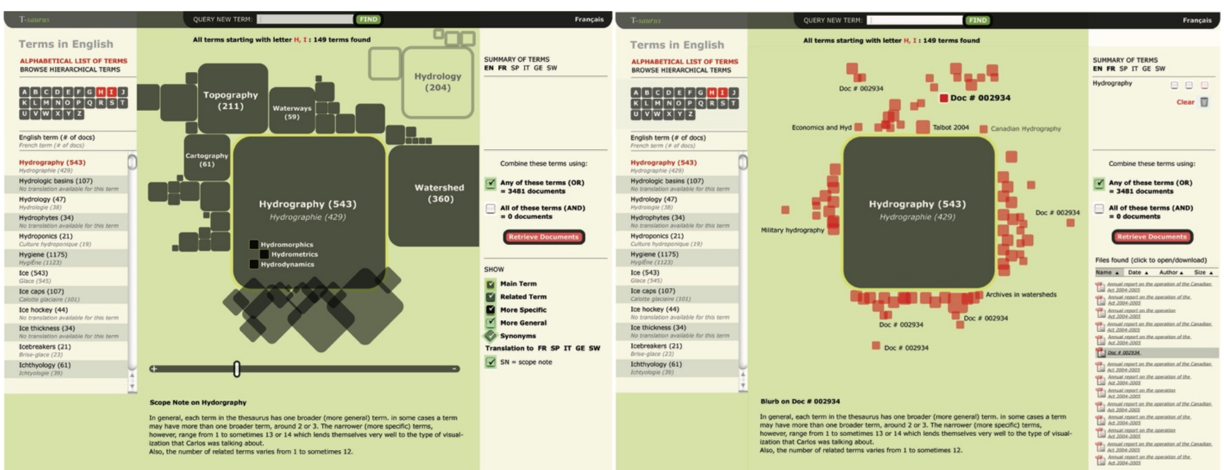


Figure 3.02. Example of a rich-prospect browsing interface: The T-Saurus, a visual browser for multilingual query enhancement (Shiri, Ruecker, Doll, Bouchard, & Fiorentino, 2011).

3.5 Additional Methods and Synergies Involved

A multidimensional and multiple method approach involves a creative and integrative way to produce research designs. As is common in other user-centered and ethnographic design methods (e.g., cultural probes), approaches should be applied with a creative attitude and developed for each purpose (Mattelmäki, 2005). While the binomial method of rich-prospect browsing and academic prototyping may seem dominant, the nature of the research question and the complexity of the project proposed to address the StrC ecosystem still require combining additional research methods and techniques to prepare, collect, administer, and analyze stages of the study. These additional methods and techniques are described in the following sections.

3.5.1 Probing, Cultural Probes, and Informational Probes

In cultural anthropology, the concept of "probing" is used as a method of inquiry for unstructured interviewing techniques (Bernard, 1995). Probing is defined as a method (of interviewing) to stimulate an informant to produce more information without having to directly interact with the researcher (Bernard, 1995). This principle can be extrapolated to cultural (Gaver, 1999; Mattelmäki, 2005) and informational probes (Crabtree et al., 2003; Hemmings, Crabtree, Rodden, Clarke, & Rouncefield, 2002) in the way that both are a sort of mediating "object" implicit in the inquiry that likewise stimulate study participants to produce more information without having to directly interact with the researcher. Probing and probes share this conceptual characteristic, with the "probe" serving as the mediating tool and "probing" as the inquisitive technique. Probes themselves suggest a variety of different techniques, as in the case of oral and prototypic probes. While oral probes are used almost exclusively in personal interviews—in which the interviewer interacts with individuals or groups in person—and they involve the use of appropriate spoken language, tone, pauses, and dialogic techniques (Hemmings et al., 2002), prototypic probes require an interface (physical or digital artifacts) to interact between the interviewer and the interviewee, establishing a physical and temporal distance between both, which may invite deeper thinking, analysis, and reflection from the interviewees. William Gaver is a pioneer in the use of such prototypic probes as a method for research (Mattelmäki, 2005), which is useful for design purposes. Among the so-called *designerly* activities (Cross, 1982), probing is considered one way of conducting a research study (Mattelmäki, 2005). According to Gaver, Boucher Pennington, and Walker (2004), "probes are collections of evocative tasks meant to elicit inspirational responses from people … [and] it's an approach that values uncertainty, play, exploration, and subjective interpretation" (p. 53). This "sense of uncertainty" can be understood as a positive value for a design process. Although cultural probes have been well accepted as a method, Gaver himself has manifested skepticism about framing probes as a formal methodology (Mattelmäki, 2005).

Design researcher Tuuli Mattelmäki (2005) describes using the probes approach as a user-centered design method in which attention is focused on improving usability and often ergonomic problems. These probes are conceived as design-oriented tool kits with exploratory goals based on self-documentation. Their characteristic is to invite and provoke users to reflect on and verbalize their experiences using the probe, which may lead them to visualize actions and contexts (Mattelmäki, 2005).

The user-centered approach alone will not provide an entirely reliable experience, especially given the diversity and nature of study participants. However, combined with other methods in the context of a biocentered approach, probes are beneficial to the StrC project (described in Chapter 4). Probes can be used to create interaction among groups of people from different disciplinary backgrounds, who are usually unfamiliar to one another (Gaver et al., 2004). This is the case with using the StrC rich-prospect ecosystem as a probe for connecting the different target audiences involved (i.e., from design and science). The concept of probes is more than a metaphor for the academic prototyping interface; the interface itself serves as a digital probe. It also shares qualities from participatory and co-design methods in a way that influences the design process by providing information and inspiration.

Using the StrC as a probe may also involve certain risks due to the openness and exploratory nature of probes. This can drive initial research expectations into unexpected directions (Mattelmäki, 2005). Although a negative outcome is a possibility, this characteristic of probes is of great benefit for the exploratory purpose of the StrC and the integrative nature of the research question. According to Mattelmäki, the strengths of the probes lie in the subjectivity and broad focus of the information gained, although weaknesses associated with the fragmented pieces of information can lead also to undesirable results (Mattelmäki, 2005, p. 94). For an academic prototyping case however, subjectivity and broad focus must be implicit in the nature of the method under a “work in permanent progress” idea, and, from such an angle, strengths overcome the weaknesses of fragmentation. A strength of the probes’ approaches is that they make it possible to get close to the user–participant and establish a dialogic relationship (Mattelmäki, 2005). Nevertheless, due to the limitations mentioned above, probes alone should not be used for the purpose of information gathering (Mattelmäki, 2005). In this sense, Mattelmäki (2005) describes case studies where probes were used in conjunction with other approaches—for example, focus groups, expert interviews, and observations (p. 94). This approach is consistent with the multidimensional and multiple method approach used in the StrC study. Taking into consideration Mattelmäki’s recommendations, the StrC prototype used during the study was not used as a tool for collecting final content but rather for detecting what and how further content could be gathered and curated to complete a comprehensive database and research experience. Accordingly, additional methods to analyze and extend participants’ responses were considered for the study too (i.e., the survey-questionnaire online and interviews).

Using the StrC as a probe may also be considered as a case of *informational probes* (Crabtree et al., 2003; Hemmings et al., 2002), which are specifically oriented to information gathering rather than just inspiration. Informational probes provide ways of gathering data and facilitating understanding among different audiences. Probes in this case are used to inform researchers and establish a conversation between the different audiences for the next research phases (Mattelmäki, 2005). The self-documenting characteristic of digital probes can be observed in the edit and contributions red layer function of the StrC (Fig. 3.03), intended to collect feedback, amendments, and suggestions by science peers.

Mattelmäki (2005) provides four reasons for the characteristics of probing: inspiration, information, participation, and dialogue (Figure 3.04). The StrC can actively cover all of these reasons; nature's cases of structural colour offered in the StrC inspire and inform designers to practice biomimetic design, while the interface offers scientists tools for participation to contribute to the taxonomic features, and opens a dialogue between scientists and designers that is currently scarce or nonexistent.

The way the StrC studies use probes, in an academic prototyping, rich-prospect browsing ecosystem context, can be seeing as a halfway method between Gaver's inspirational cultural probes and the informational probes proposed by Hemmings et al. (2002). On one hand, the StrC as a probe provides opportunities to discover new forms of sociability, and new cultural —and interdisciplinary—forms of communication (Gaver, Dunne, & Pacenti, 1999). On the other, it identifies and collects valuable data and feedback, useful for objective research. Another element from probing that aligns with the idea of the StrC is considering aesthetics to be an integral part of functionality that lead, equally, to efficiency and usability (Gaver et al., 1999).

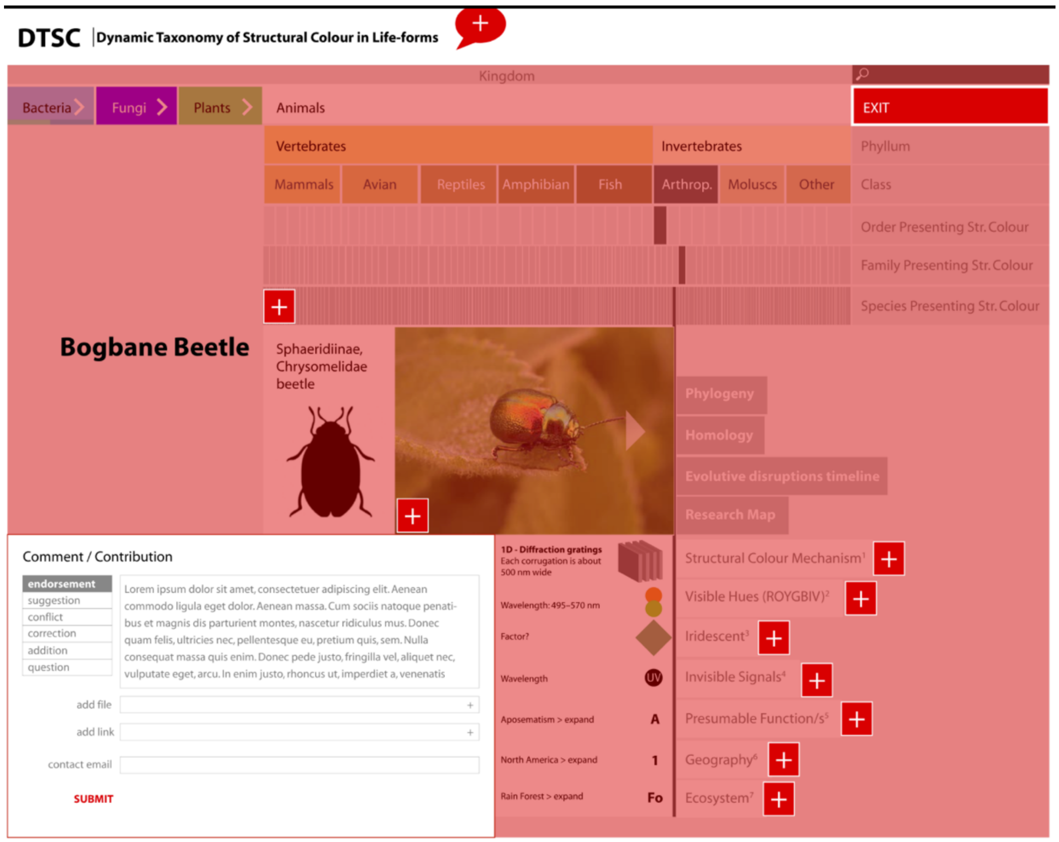


Figure 3.03. Edit/contributions red layer option on top of a species profile page in the StrC (former DTSC) interface (image taken from the design mockup version). This function is for science peers to offer feedback and suggestions on the taxonomic features shown, and plays a similar role to the self-documenting characteristics of digital probes.

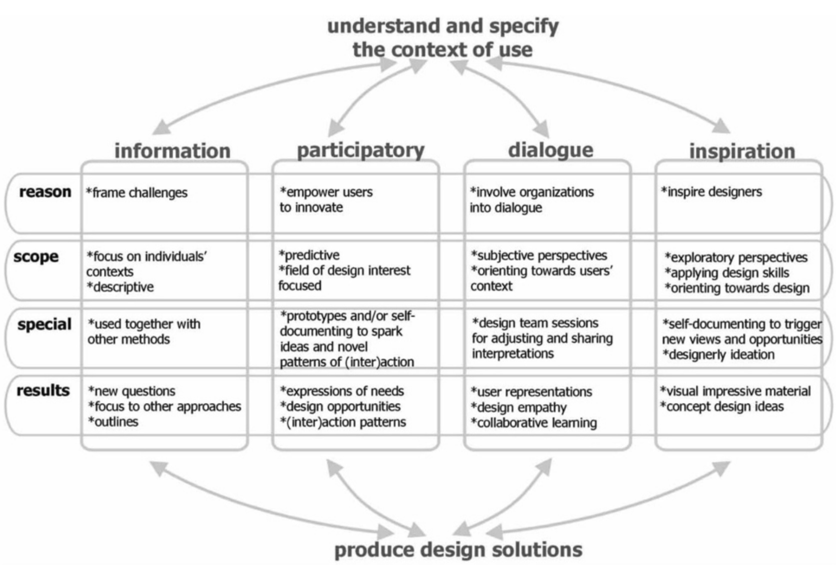


Figure 3.04. Four reasons for using the probes approach in reference to human-centered design process according to Mattelmäki (2005). The StrC has the potential to explore all these aspects.

3.5.2 Data Visualization Techniques as Hermeneutical Tools of Interpretation

Data visualization techniques, such as word-clouding, tree-maps, and text mapping, are considered part of the computer-assisted or digital world useful for pattern recognition, analysis of distribution, impact, proportions, et cetera. The collaborative nature of computer-assisted research methods requires a variety of skills to develop tools of interpretation and analysis (Rockwell & Sinclair, 2016). This is commonly seen in the humanities computing and data visualization design realms, in which multidisciplinary teams involve more than computing, text, data, or design specialists to achieve research goals. Collaboration in such projects can take a variety of forms and present a variety of visual results, which can become "visual techniques of interpretation." These techniques can be considered new hermeneutical tools for research (Rockwell & Sinclair, 2016) to pursue testing new ideas, posing new questions, and discovering new research directions. The analogy of these visual techniques to hermeneutics—the field of theory and methodology of interpretation—relies on such an exploratory, reflecting, and collaborative environment to produce new ways of knowledge. The "artifacts" of study in these cases can be approached as a special form of texts for a hermeneutical procedure (Hodder, 1994) which, in combination with visual elements (photographs, illustrations, diagrams, and other visual metaphors), completes a hermeneutical exercise experience.

The StrC interface provides visual tools for interpretation presented as additional visual "widgets" that follow the concept of analysis, interpretation, and reflection proposed by other hermeneutical tools for research observed in the digital humanities and data visualization design (e.g., the word-cloud of authors for a specific species page, the "sunword" visualization[52] of the

[52]"Sunword" is a "wiki" text visualization tool or information glyph designed to support collaborative editing. It was part of a series of digital tools designed for a study on wiki collaboration research conducted by a multidisciplinary group at the University of Alberta (Arazy et al., 2010).

homology widget, et cetera—all functions described in Chapter 4). But these hermeneutical visual techniques are also an important part of the data analysis done for the study. Data collected for the study (see Chapter 4.8) is "hermeneutically translated" into colour-coded, pattern-revealing, grouping, repetition, and variation techniques, to identify meaningful qualitative information gathered from the study participants (see Chapter 4.10).

3.5.3 Fieldnotes

Fieldnotes are very common in anthropology and other fields in the humanities in qualitative research (Emerson et al., 1995). Some researchers consider taking fieldnotes especially useful as an additional source for recalling experiential memories at the time of conducting their studies, while others consider fieldnotes much less valuable and "disposable" materials, compared to the much more real visual and aural qualities that personal experiencing can bring to our memories (Jackson, 1990). In any case, fieldnotes can serve as a mediation tool between reality and thesis, and memory and publication (Jackson, 1990), that can contribute to a better recollection of facts from personal contact with research events.

Taking fieldnotes while conducting different stages of the StrC prototype development and studies helped to harmonize the material collected, and to build a narrative from the whole experience of conducting research. While this may seem a collateral technique, and not at the core of the methods used for the study, it also implied a conscious strategy of recording, sampling, and writing notes throughout the process, which informed the writings of this dissertation. This process already started in the early stages of this research program when different activities related to the preparation of the StrC prototype were experienced. From this process, notes, sketches, quick diagrams, and photographs were taken and saved as fieldnotes (Fig. 3.05).

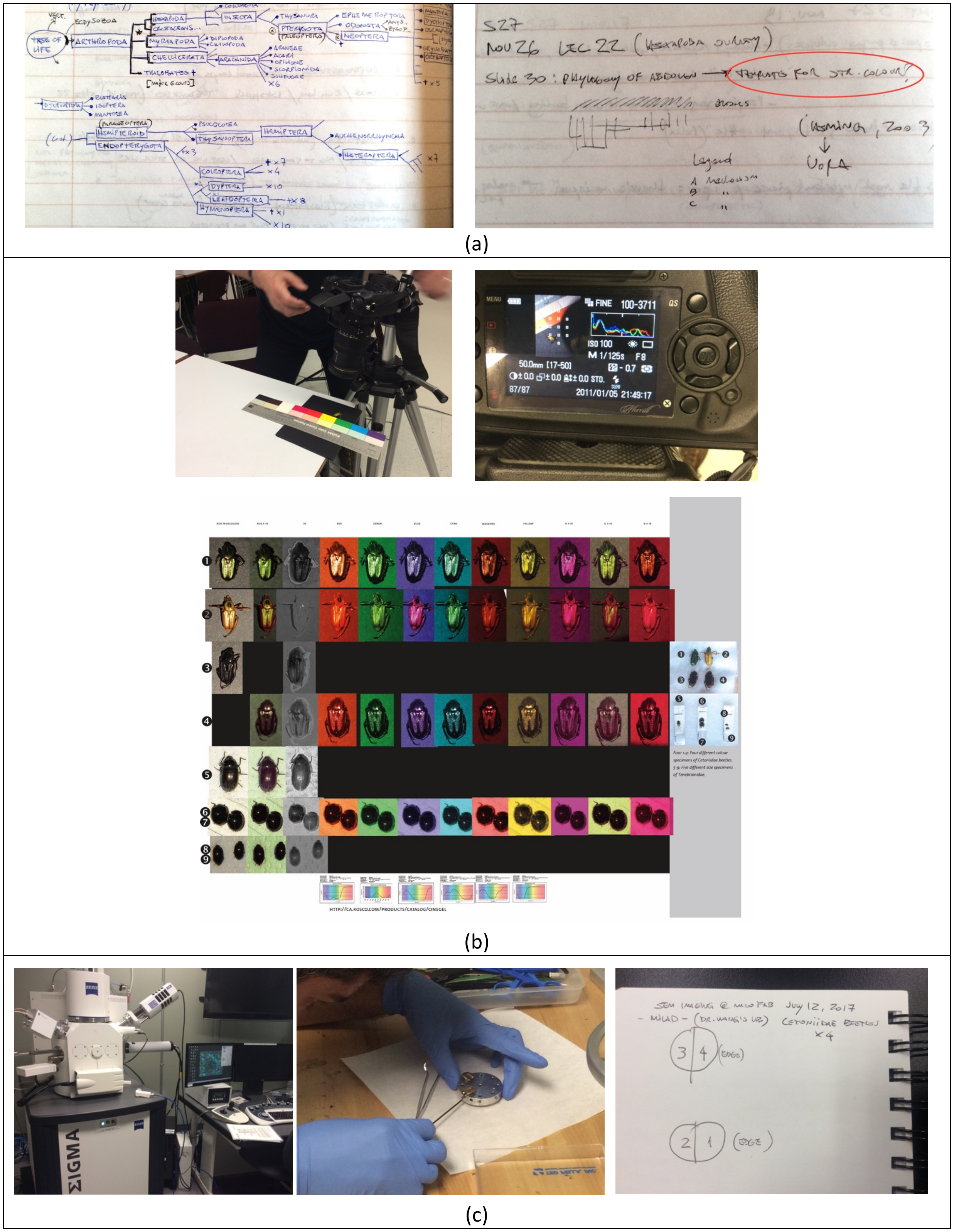


Figure 3.05. Fieldnotes collected during preparation of the StrC content and prototype: (a) First steps on creating a taxonomy on structural colour concept, diagrams, and notes on the first “Taxo-Phylo” idea; (b) Setting up of Foveon shooting and compilation of IR Foveon images taken to create samples for a dataset template. The samples used for

the initial dataset were provided by Dr. Terzin from his collection of coleoptera; (c) Photograph of scanning electron microscope (SEM) equipment used at the University of Alberta NanoFAB, and preparation of samples to create SEM images for the StrC dataset template. SEM images are an important visual cue to understand the structural colour mechanism present in different species. SEM imaging demands special preparation of samples prior to the scanning process as a thin layer of gold is added to each sample. This process requires a special number of coding and tracking processes to recognize the samples, all now gold-covered and hard to distinguish otherwise.

3.5.4 Observational Techniques for Diagrammatic and Taxonomic Representations

A basic feature of any taxonomic procedure is to describe the objects of the study comprehensively. The elements used for this purpose should be as simple as possible (de Hoog, 1981). A taxonomy is also an attempt to make sense of complexity by adding order to an apparent disordered or fragmented sample of information. The human mind possesses the ability to intuitively produce classifications and holistically sense complexity, as the Gestalt theory suggests.[53] According to de Hoog (1981), taxonomic ordering is an experimental science, not a descriptive one. As such, the dynamic nature of taxonomic classification invites one to explore different methodological angles, to create order and facilitate understanding. This happens not only by describing content, but by creating possibilities to play with content and reveal new angles.

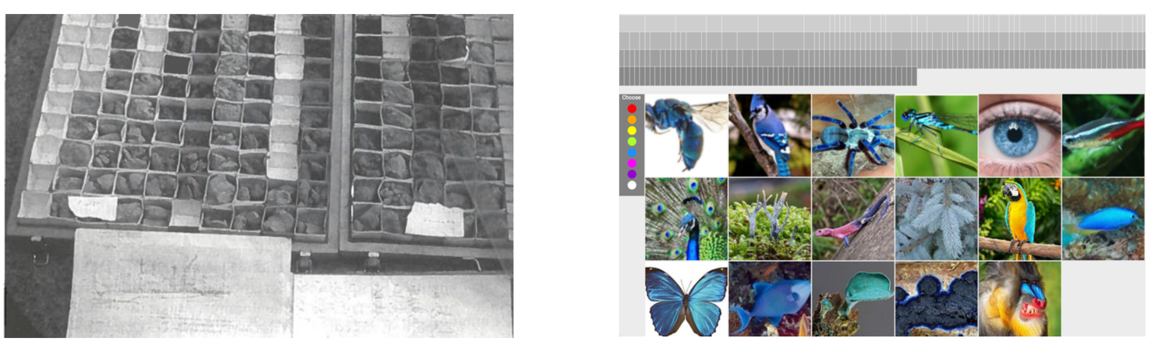
In the *Pandora's Hope* chapter, "Circulating Reference: Sampling the Soil in the Amazon Forest," Bruno Latour (1999) explores how scientists pass from ignorance to certainty by organizing samples from nature in a taxonomic and comprehensive way, a sort of a cabinet artifact dedicated to store collected species referred to as a "pedocompactor," from the word pedology[54] (p. 47). This concept demands dividing a section of the forest into a coordinated grid to which the pedocompactor corresponds. The physical nature of the "in-situ" visualization and the created artifact respond to a taxonomical interpretation guided by the scientific method. As a result, this method offers a rich two-dimensional diagram of colours, textures, and emerging patterns (Fig. 3.06a). The process of organizing the data (selecting, centering, coding, cleaning,

[53] Gestalt is defined as "a configuration or pattern of elements so unified as a whole that it cannot be described merely as a sum of its parts" (https://dictionary.cambridge.org/dictionary/english/gestalt). The perception of oneness from many is the basis of Gestalt. It is derived from the 1890 German philosophy of *Gestaltqualität*, meaning "form or shape," which explored the idea of perception.
[54] Pedology is a branch of botany that study soils in their natural environment.

etc.) becomes a transformation process (Tufte, 1983), and it reveals features that were previously invisible (Latour, 1999).

Latour (1999) observes and takes photographs, as fieldnotes, of what is described as an attempt to order "the jungle of scientific practice" (p. 24). This effort to understand how science observes nature, and how this can be translated into a visual representation of some order, describes very well what it takes to create an ecosystem like the StrC (Fig. 3.06b).

The sciences may not speak of the world directly, but instead construct representations of it (Latour, 1999) or allow the scientific work to be represented by other means, such as simultaneous visualization of data (e.g., rich-prospect browsing). Latour (1999) suggests that "one science always hides another" (p. 32); the pedocompactor concept is, in its way, an example of the kind of outcomes that this idea implies. The artifact serves as a taxonomic visualization of the terrain explored, an information design method representing a scientific method. Both disciplinary realms (i.e., visual communication and biology in the case of this research project, anthropology and botany in Latour's case) learn from each other to adapt and better understand the information available through observation and experience. In cases like this, when multiple disciplines join efforts to acquire new knowledge, observation and experience may not be different concepts, and both can be seen as constructions (Latour, 1999).



(a) (b)

Figure 3.06. (a) Pedocompactor table with soil samples (Latour, 1999); (b) Taxonomic collection of structural colour grouped by hue under the StrC environment (screenshot taken from current prototype).

3.5.5 Hybrid Ethnographic Methods: Visual Layering and Composing

The users of digital interfaces (e.g., a computer user) are multimedia makers, and digital technologies shape how they imagine, construct, and exchange ideas. This interdependence gives rise to a new hybrid language that uses visual rhetoric (Coover, 2011). Among the processes that give this visual language its main characteristics are layering and composing. Layering and composing digital information are processes of interpretation and remaking. In ethnographic terms, layering and composing are a sort of "montage" of ideas, similar to what ethnographers do when "translating" cultural experiences (Coover, 2011).

The use of visual metaphors is an active part of dynamic environments such as websites, apps, or videogames (e.g., "opening windows," "drag and drop folders," "click-on buttons," etc.). The concept of rich-prospect browsers (as described in Section 3.4) aligns with the idea of visual metaphors present in digital interfaces, in that both can be seen as tools for gathering fragments of an experience into a unified whole through multimedia processes of scrolling, selecting, juxtaposing, linking, et cetera. The user of such digital environments is able to customize the experience based on particular needs. Layering and composing elements chosen from a browsing experience offer the researcher opportunities to visualize, recognize, and discover details, patterns, and whole concepts that otherwise would be difficult if not impossible to detect from fragmented, encoded, and non-visual sources of information (e.g., individual articles, books, etc.). Through its different visualization features and tools, the StrC interface offers a visual layering and composing experience for the user-researcher to interpret.

3.6 Case-Study Research Strategy

Case studies used as a research strategy "comprise an all-encompassing method with the logic of design incorporating specific approaches to data collection and to data analysis" (Yin, 2012, p. 13); accordingly, "the case study is not either a data collection tactic or merely a design feature alone but a comprehensive research strategy" (Yin, 2012, p. 13). The academic prototype/rich-prospect browsing/probing method applied through the StrC can also take the form of a case study research technique that uses an inductive process for inquiry. This approach creates the opportunity to evaluate analog cases for the StrC, such as some of the repository collections considered to populate the StrC database which also have visual interfaces, or AskNature.org, which constitutes the only case with scientific information specifically oriented to biomimetic practitioners. The study designed to work with the StrC can also serve as a template to study other interface cases.

There is a necessary distinction to be made between case study and ethnographic methods (e.g., academic prototyping, fieldnotes, etc.), in that the first can be based on mixing quantitative and qualitative evidence, while the second is essentially qualitative research (Yin, 2012). In addition, case studies can involve indirect and subjective observations instead of the detailed observations that ethnographic methods usually use as a source of evidence (Yin, 2012).

3.7 Conclusion

This chapter reviewed relevant "ways" and "methods" depicted from different epistemologies with the intention to integrate and explore synergies between diverse perspectives under the "multidimensional approach" involved in this research. These epistemologies influenced the way this research was designed and executed, and the multidimensional approach led to the use of multiple methods. A multidimensional approach implies a design generalist approach, a human ecology and material culture (more holistic and integrative) approach, and a biomimicry (scientific-design-oriented) approach.

Examples in this chapter showed how the multiple methods chosen work together and in sequence to address the different stages of the study: collecting, managing, and analyzing data. These descriptions serve as an introduction to Chapter 4, which is focused on describing the phases of the research study; the targeted participants for the study; and details about data collection procedures, data types classification, and data analysis; and the design, logistics, and implementation of the academic prototyping case (the StrC).

Under the influence of the different epistemologies involved and a multidimensional methodological approach, this research project involved a number of concepts and methods summarized as follows:

1. Biomimicry as a precedent-based design methodology: Life Principles and the biology-to-design approach to inspire.
2. Academic prototyping concept: facilitating the production and sharing of new knowledge about the science of structural colour through the design of an experimental prototype—the StrC.
3. Rich-prospect browsing: as a digital tool to pair with the academic prototyping concept, to connect the science of structural colour with designers. The StrC is a digital ecosystem of rich-prospect browsing tools for research.
4. The concept of informational probes inspired the way the StrC was implemented: as a rich-prospect browser used as an academic prototyping probe. The StrC tested as a probe established a physical and temporal distance between the research and the participants, in a way that invited deeper analysis, and reflection from the interviewees.
5. The StrC interface uses data visualization techniques as hermeneutical tools of interpretation. These techniques were also used to illustrate the findings of the StrC study in Chapter 5.
6. At multiple stages of this research project, a number of variations of field notes were used as an additional method to support the investigation, development of the prototype, and execution and follow up of the study.

7. Other additional methods and concepts helped to design the StrC experience: diagramatic and taxonomic representations, hybrid ethnographic methods (e.g., visual layering and composing).
8. The StrC was also inspired by case study research, a technique that uses an inductive process for inquiry. A case study research technique created the opportunity to evaluate analog cases for the StrC (i.e., the repository collections considered to populate the StrC database).

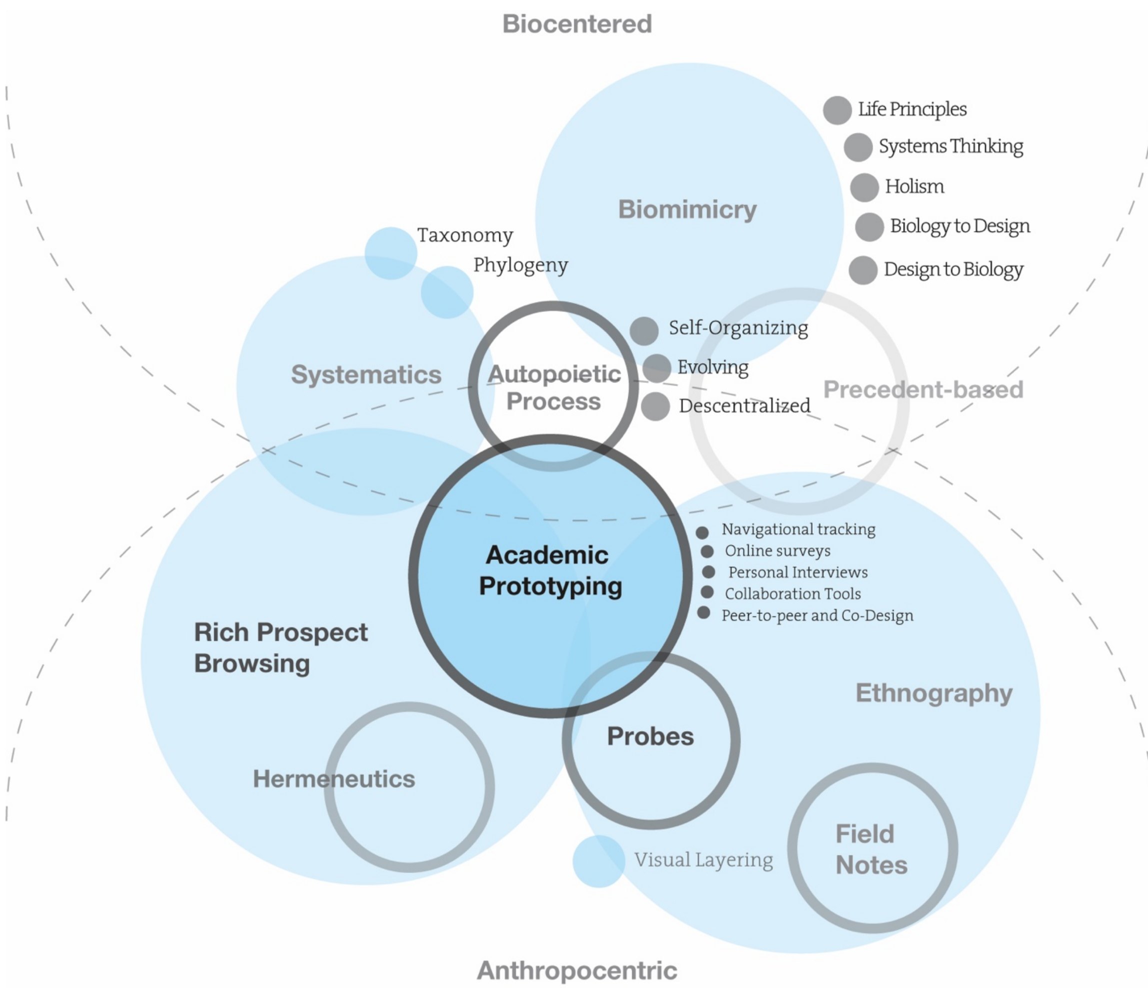


Figure 3.07. Visual representation of the multidimensional methodological approach, which gathers multiple methods and strategies used for the StrC study.

CHAPTER 4: STUDY—TESTING THE StrC, A RICH-PROSPECT TAXONOMY ON STRUCTURAL COLOUR

This chapter describes the design stages, logistics, and implementation of the Rich-Prospect Taxonomy on Structural Colour (the StrC) as an academic prototyping rich-prospect browsing interface. This interface was used as a digital probe to conduct the study. The study was guided by the two-part correlated research question: How can a biocentered design approach to colour help bridge gaps between scientific knowledge and biomimetic design practices? How can available scientific information/knowledge on structural colour be better organized and more accessible to bridge such gaps? The study explored ways and found opportunities to bridge scientific knowledge and potential biomimetic design applications.

This first section gives the necessary background on taxonomies, phylogenies, and tree thinking (Baum & Smith, 2013) as guiding concepts to facilitate the gathering of scientific information on structural colour. The second section of the chapter lists 13 suggested precedent cases of taxonomic databases and repositories, conceptually or functionally related to the StrC, and strategically targeted to be accessed in future development of the StrC. In the third and fourth sections, initial scientific questions were anticipated and formulated as a consequence of the academic prototyping process, and an initial assumption regarding the research question was enriched with new inquiries.

The fifth section describes the entire process of designing and developing the StrC prototype. The initial stage of the design process of the interface's visuals are illustrated with flow charts and diagram figures from the project, and sketches of the interface design stages. A mockup version of the interface and supporting materials for the programing and development stages of the prototype can be found in section 7.2 of the Appendices. This stage also describes the preparation of datasets that made it possible to populate the database with initial data, and made the different modules of the prototype functional for testing purposes. This stage involved contributions from different epistemologies and areas of expertise (e.g., entomology, scientific photography, electromicroscopy, and physics-optics). This part of the chapter also describes the programming stages of the initial prototype and database that were first developed as a cohort computing science project. It goes on to describe the full development and deployment of the final prototype for the study (https://strc.online). This final prototype was programmed by two computing experts and has specific features and advanced functions not included in the initial stages (e.g., the peer-reviewing and contribution mechanism, and new administrative functions added to the backend).

The last sections of the chapter are dedicated to the planning, execution, data collection, data analysis, and data classification of the study. It describes how the different parts of the study were organized; how the prototype was used; and also the logistics, materials, and preparation needed to run the study.

4.1 Taxonomies, Phylogenies, and Tree Thinking

The StrC interface was initially named DTSC, for Dynamic Taxonomy on Structural Colour, which makes sense for the nature of the tool developed for the study. However, there was a fundamental redundancy implicit in the name, in that every taxonomy in science ***is*** dynamic. This dynamism is given by the experimental nature of building a taxonomy; taxonomic ordering is an experimental, not a descriptive science (de Hoog, 1981). As such, taxonomies try to add order and simplicity to increasing information, knowledge, and complexity. In this sense, the dynamism of rich-prospect browsers facilitates addressing the task.

4.1.1 Taxonomy

Taxonomy is a science exclusively devoted to the order of complex data, particularly appealing to scientists due to the aesthetic characteristics resulting from the visual structure that taxonomies produce from data. This is a clear example of how aesthetics, in addition to subjective values, can be also functional and effective at delivering information. Taxonomic categories work as levels of hierarchical classification (Simpson, 1961) to produce these visual structures. A taxonomy consists of three fundamentally different parts: a nominal, reproducible representation; a logical, verifiable ordering; and a nomenclature guided by practical application (de Hoog, 1981).

1. *A nominal, reproducible representation*. The StrC uses species as nominal units represented in the main, rich-prospect visualizations, gathered by taxonomic order, and also represented at the species-profile pages.
2. *A logical, verifiable ordering*. The StrC uses essential taxonomic categories from biology to provide the structure with a logical and verifiable ordering, on the main page of the rich-prospect browser. In biology the main taxonomic categories, grouping from the overall to the particular, are Kingdom (Animalia, Plantae, Bacteria, Fungi), Phylum (e.g., Arthropods, Molluscs, etc.), Class (e.g., Mammals, Fish, Insects, etc.), Order (e.g., Coleoptera, Lepidoptera, etc.), Family (e.g., Hominidae, Scarabaeidae, etc.), Genus (e.g., Canis, Felis), and Species (e.g., Homo Sapiens, Morpho melenaus, etc.). A complete list of taxonomic hierarchies includes supra, sub and infra categories too (e.g., supraclass, class, subclass, infraclass), although these are not included in the StrC.
3. *A nomenclature guided by practical application*. The StrC uses a combination of vernacular (e.g., species common names) with scientific vocabulary to provide an understandable nomenclature for a broader audience, guided by practical application.

4.1.2 Tree Thinking

Tree thinking (Baum & Smith, 2013) influences the way the StrC interface works, providing tools for exploring and making connections to the evolutionary features of the structural colour taxonomy. Tree thinking is “the ability to visualize evolution in tree form and to use tree diagrams to communicate and analyze evolutionary phenomena" (Baum & Smith, 2013, p. 1). There is strong evidence from science that the evolutionary story of life nearly always involves the branching of lineages (Baum & Smith, 2013). This supports the use of trees as a visual representation of evolution. In cases like the StrC widget *Phylogeny* (Fig. 4.01) or *Evolutive Disruptions* (Fig. 4.02), tree thinking is helpful to organize the available knowledge of biological diversity for the collection's selected and grouped examples (Baum & Smith, 2013). Other ways of visually representing lineage (e.g., more linear and less "branchy," such as "ladder of life" or "Great Chain of Being") would be relatively ineffective to build these kinds of interacting visualizations (Baum & Smith, 2013) due to their limitations in illustrating connections and relationships.

4.1.3 Phylogenetic Modelling

Phylogenetic modelling is usually proposed by systematics studies[55] from biological sciences (Baum & Smith, 2013). Phylogenetic trees make it possible to visualize history traits of evolution and discover general patterns (Baum & Smith, 2013). Sometimes they also make it possible to reconstruct the evolutionary changes that would otherwise be unnoticeable or fragmented in certain species. Applied to structural colour, phylogenetic representations can help researchers to understand the degree of relatedness of given taxa aligned to a common evolutionary history, and how that history is linked to the evolution of colour mechanisms. The intention of the StrC widgets like *Phylogeny* or *Evolutive Disruptions* is to provide a phylogenetic tree approach to find and visualize commonalities, patterns, anomalies and

[55] Systematics is the scientific study of the kinds and diversity of organisms and all the relationships among them (Simpson, 1961).

disruptions in the evolution of species under certain characteristics of colour presence, colouration mechanisms, and apparent or verified colour functions.

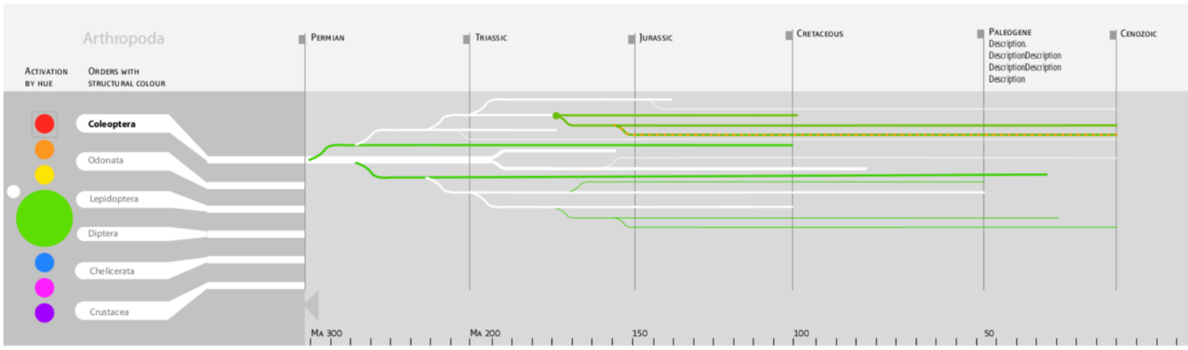


Figure 4.01. Mockup version of the Phylogeny widget.

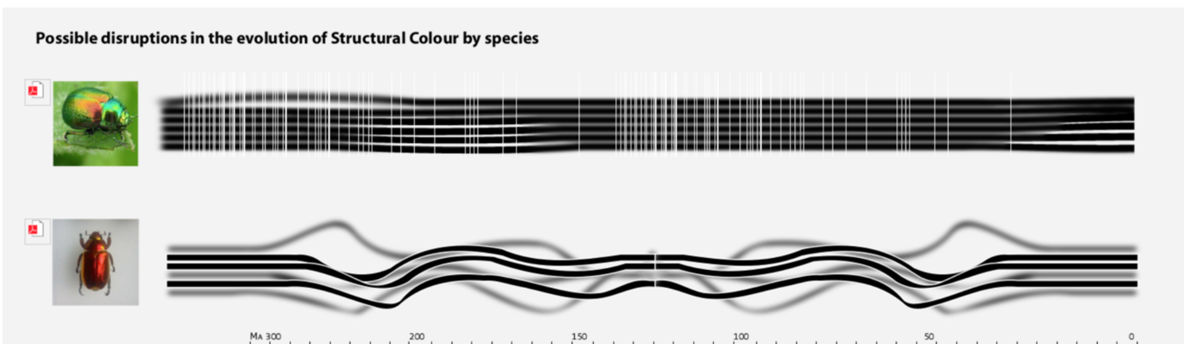


Figure 4.02. Mockup version of the Evolutive Disruptions widget.

Taxonomic classification and phylogenetic modelling are useful to inform biomimetic design processes. As described in Chapter 3, the transfer of scientific knowledge from biology methods to design is more rigorous than the services that design brings to scientific methods (Helfman Cohen & Reich, 2017; Sartori et al., 2010). Therefore, a design challenge may not impact the way the rigour of the scientific method is led to inform the design process, but the scientific method may certainly influence how the design process results in innovative solutions. Thus, the design of the StrC is inspired in biological taxonomy and evolutionary phylogenies, but it is unlikely to provide new ways of doing taxonomic and phylogenetic research in science. Ideation stages of the interface were strongly influenced by science, and this influence has shaped the outcomes of the design process. Edward Tufte (1983, 1990) explored this influence in information design projects, supported by the understanding of taxonomic method as an experimental science (de Hoog, 1981).

4.2 Summary of Precedent Taxonomic Databases and Repositories

For a period of 5 years, many examples of biological data repositories and taxonomic databases have been identified as case studies to inform this research project. Some of them are interrelated, like the case of the Encyclopedia of Life initiated by E.O. Wilson in 2007, used as a resource by AskNature.org launched by The Biomimicry Institute in 2008. From the multiple available sources to access free data in the form of text, images, and metadata (including free sources such as Wikipedia and Google), 13 cases have been selected to inform and be used as a resource to populate the StrC database. Potentially, many of these databases will be also accessed to automatize the collection of data and metadata to expand the currently small StrC dataset to a comprehensive database in the future. The following list summarizes these precedents:

1. Boldsystems.org—Barcode of Life Data System (University of Guelph)[56]
2. iNaturalist.org (California Academy of Sciences and the National Geographic Society)[57]
3. Webofscience.org[58]
4. Treeoflife.org[59]

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[56] *The Barcode of Life Data Systems* (BOLD) is an informatics workbench aiding the acquisition, storage, analysis, and publication of DNA barcode records. BOLD is freely available to any researcher. BOLD is a web-based delivery and flexible data security model. It is also well positioned to support projects that involve broad research alliances. (www.barcodinglife.org).

[57] *iNaturalist* is an online social network of people sharing biodiversity information to help each other learn about nature. It is also a crowdsourced species-identification system and an organism-occurrence recording tool. Users can use it to record their own observations, get help with identifications, collaborate with others to collect information for a common purpose, or access the observational data collected by iNaturalist users.

[58] *Web of Science* (previously known as *Web of Knowledge*) is an online subscription-based scientific citation indexing service originally produced by the Institute for Scientific Information (ISI), later maintained by Clarivate Analytics (previously the intellectual property and science business of Thomson Reuters), that provides a comprehensive citation search. It gives access to multiple databases that reference cross-disciplinary research, which allows for an in-depth exploration of specialized sub-fields within an academic or scientific discipline. (https://en.wikipedia.org/wiki/Web_of_Science).

[59] The Tree of Life Web Project is an Internet project providing information about the diversity and phylogeny of life on earth. This collaborative, peer-reviewed project began in 1995, and is written by biologists from around the world. The site has not been updated since 2011; however the pages are still accessible. The pages are linked hierarchically, in the form of the branching evolutionary tree of life, organized cladistically. Each page contains

5. ITIS.gov[60]
6. EOL.org (Encyclopedia of Life)[61]
7. VTech Structural Colour DB (Virginia Institute of Technology)[62]
8. EDIT Cyber-Taxonomy Platform (European Distributed Institute of Taxonomy)[63]
9. Strickland Museum DB (University of Alberta)[64]
10. NHM Natural History Museum, London (Entomology Collection)[65]
11. Project Plumage—Zooniverse.org (University of Sheffield, ERC, NHM)[66]

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information about one particular group of organisms and is organized according to a branched tree-like form, thus showing hypothetical relationships between different groups of organisms. In 2009 the project ran into funding problems with the University of Arizona. Pages and treehouses submitted took a considerably longer time to be approved as they were being reviewed by a small group of volunteers, and, apparently, around 2011, all activities ended (https://en.wikipedia.org/wiki/Tree_of_Life_Web_Project).

[60] ITIS stands for the *Integrated Taxonomic Information System* and it is the result of a partnership of federal agencies formed to satisfy their mutual needs for scientifically-credible taxonomic information. The goal of ITIS is to create an easily accessible database with reliable information on species names and their hierarchical classifications. The database is reviewed periodically to ensure high quality with valid classifications, revisions, and additions of newly described species. The ITIS includes documented taxonomic information of flora and fauna from both aquatic and terrestrial habitats. (https://itis.gov/info.html).

[61] EOL provides global access to knowledge about life on earth. Its goal is to increase the awareness and understanding of living nature through an *Encyclopedia of Life* that gathers, generates, and shares knowledge in an open, freely accessible and trusted digital resource. It provides access to the knowledge at a granular level using faceted search tools and data services in commonly used formats. It is a collaboration tool with data hubs worldwide to support interoperability and sharing. (https://eol.org/docs/what-is-eol).

[62] The VTEC database combines scanning electron micrographs, visible light photographs, UV-VIS colour reflectance spectra, and structural measurements of specimens from the Virginia Tech Insect Collection (VTEC). It also includes citations of previous research on each insect's cuticular colour. (http://iridescent.life).

[63] The EDIT Platform for Cybertaxonomy is a collection of open source tools and services which together cover all aspects of the taxonomic workflow. It covers collections and specimens, descriptions, fieldwork, literature, and geography, among other areas. At the heart of the Cybertaxonomy platform is the *Common Data Model* (CDM), a repository for every conceivable type of data produced by taxonomists in the course of their work, and the back-end for most EDIT components. (https://cybertaxonomy.eu).

[64] The E. H. Strickland Entomological Museum houses approximately one million specimens. The research collection includes principally Nearctic insects. The beetle family Carabidae includes about 400,000 specimens mainly from the Nearctic region, but with an important Neotropical component, and fewer taxa from the remaining biogeographic regions. Another group of major interest is that of the moths and butterflies, order Lepidoptera, with nearly 75,000 specimens, about 41,000 of which are from Alberta localities. The E. H. Strickland Museum collections are available at the Virtual Museum: http://www.entomology.museums.ualberta.ca.

[65] The NHM Natural History Museum is a world-class visitor attraction and leading science research centre. It offers unique collections with more than 80 million specimens (http://www.nhm.ac.uk/our-science/collections/entomology-collections.html).

[66] This project aims to measure the dazzling array of plumage colouration in birds to gain a better understanding of how and why animal colouration evolves. Key questions are at the core of this research, such as: how colourful are birds? How quickly does plumage colour evolve? Are evolutionary changes in plumage colour associated with the origin of new species? (https://www.zooniverse.org/projects/ghthomas/project-plumage/about/research)

12. PeTaL Periodic Table of Life (V.I.N.E. NASA)[67]

13. AskNature.org (Biomimicry Institute)[68]

From these repositories, the StrC would collect data on:

- More species with structural colour (common name, scientific name, and phylogeny)
- New details on structural colour mechanisms
- Information on geolocation, ecosystem, weather, et cetera, for specific species
- New scientific literature (titles, publishing details, authors, abstracts, and access to documents)
- New photographic material of species in high-resolution
- Available Scanning Electron Microscopy (SEM) and Transmission Electron Microscopy (TEM) imagery
- Available Hyperspectral imagery including ultraviolet (UV) and infrared (IR)
- Different spectra from different light conditions
- Details on iridescence
- Metadata on specimens
- Presumable functions discussed or known
- Wavelength range, frequency range, photon energy range, reflectance, and luminosity
- Institutions, labs, and researchers working on structural colour

[67] PeTaL (*Periodic Table of Life*) is intended to be a design tool to enable the systematic design of nature-inspired systems. This requires vast quantities of high quality data, images, videos, publications and other forms of input. A large user base is also needed to obtain feedback and to ensure PeTaL's value to various user demographics and design philosophies. V. I. N. E. (*Virtual Interchange for Nature-inspired Exploration*) was created to meet the aforementioned requirements for PeTaL on August 2, 2016, by establishing a convergence of practitioners, disciplines, bio-inspired philosophy, tools and research (https://www.grc.nasa.gov/vine/about/what-is-vine-2/).

[68] AskNature.org is an online database launched by The Biomimicry Institute and aimed at making nature-inspired ideas more accessible. AskNature.org is a free, online database of nature's solutions with hundreds of described processes. Each entry includes an explanation of a strategy, information on organisms that utilize the strategy, real or possible products and uses for the strategy, and related photos, illustrations, references, and experts (AskNature.org).

As suggested by study participants (see details in Chapter 5.1.2.1.2, p. 173), accessing external databases will allow the StrC to automize a cross-checking and self-correcting mechanism to improve the accuracy of data and details available about each species.

4.3 Scientific Questions That Have Arisen

In conversations before the study began, some of the scientists who eventually contributed raised initial questions about the impossibility of completing an entire collection of species with structural colour, due to two main limitations: (a) the existent taxa on structural colour is incomplete, and new discoveries (either new species or new structural colour features in known species) happen on a regular basis;[69] and (b) even if all the possible species with structural colour are discovered and classified, and the data is available to be collected, scientific consensus on the nuances of structural colour mechanisms, functions, and explanations may still be inconsistent, and an important part of this discussion is relatively speculative.

Far from compromising the nature of the StrC project, these questions enrich the purpose of using an academic prototyping tool to encourage exploration, speculation, discovery, discussion and, ultimately, new agreements. The proposition of the StrC itself seems as vast as any taxonomy of life, with the difference that the final goal is not to have a final goal, but to open a process to indeterminately connect the science behind structural colour with opportunities for design innovation.

As presented in the literature referenced in Chapter 2, the phenomenon of colour has been of deep interest since the times of the Greek philosophers, and has been vastly studied by enlightenment scientists and contemporary colour theorists. But these fundamentally

[69] Various developmental processes contribute to the same or similar outcomes in terms of structural colours. For example, most insects undergo metamorphosis while most vertebrates develop directly, without a larval stage. Sometimes certain larval stages expresses structural colours, for example the Chrysalis or pupa of butterflies, which often is iridescent (T. Terzin, personal communication, June 4, 2019).

philosophical approaches are taken to a new level of questioning when scientific discoveries provide new evidence of the colour phenomenon present in life phenomena. Initial questions proposed from a biomimetic design perspective served as guiding questions to design the StrC functions and study. These questions involve topics about which science inquires, discusses, and investigates: What is the purpose or are the purposes of structural colour in the identified species? What strategies in nature take advantage of the ability to read structural colour and why? Why did some species evolve from pigmentation to structural coloration mechanisms? Why did so many diverse species, with different external stimuli and from entirely different ecosystems, converge with similar structural colour mechanisms? Why can different structural colour results be observed within the same species? How can all these evolutionary features of structural colour be explained in comparative problem-solving terms? These questions may not be completely addressed by the study; however, they are implicit in the use of the StrC as an exploration tool. Triggering or igniting such questioning is at the core of the StrC, and pursuing answers may lead to new discoveries. Some of these questions were present in the participants' insights as reported in the survey and the interviews conducted at the end of the study, as described in Chapter 5.

4.4 Identifying the Science–Design Gap

Key elements and features of the StrC interface were designed to detect evidence of interdisciplinary gaps that may prevent biomimetic designers from accessing information that would enable them to advance in structural colour implementation (in design materials, products, services, etc.). The study proposed using the StrC interface as an academic prototyping *probe*. This probe was shared with study participants of the study, and shaped by the feedback obtained from the exploration. In many aspects the study results helped to prove the focus of the study, and in other aspects to challenge it: the existence of disciplinary gaps, and the possibility of addressing them by designing a tool for research (the StrC). Chapter 3 identified three main aspects as subjects of analysis. These aspects, which were identified from the data collected in the study, are:

1. Scientists' level of interest in exploring and contributing to the StrC.
2. Professional practitioners' and researchers' level of interest in biomimetic design as a means to explore the StrC and the subject of structural colour, following a "biology to design" biomimicry approach.
3. Using an evaluation of commonalities and convergences in the collected data to detect synergies between scientists and professional practitioners and researchers interested in structural colour and biomimetic design.

The data collected from the participants' interaction with the interface, and the responses to the semi-structured questionnaires and interviews (Bernard, 1995) revealed some specific details that address the main assumption of the gap and link to the research question, as it is fully developed in Chapter 5. Specific components of the StrC were designed for this underlying purpose, and the results measured from the study gave good elements to contrast and analyze the following initial pre-study assumptions:

- The number of contributions and amount of feedback entered by scientists to the *red layer* function suggests there is a level of engagement with the StrC as a research tool to communicate scientific knowledge.
- Scientists exploring details of the species profile and widgets may detect opportunities to provide feedback on misunderstanding and misconceptions about structural colour mechanisms and variations.

- The number of visits to specific StrC sections or features from scientists compared to designers may support the idea that some aspects considered trivial for one may result in aspects considered vital for the other and vice versa.
- The time spent by scientists interacting with the main taxonomy versus interacting with the collection of photos ordered by colour could be inversely proportional to the time spent by designers interacting with the same features: this may suggest that scientists tend to explore data, while designers tend to explore visual cues. Scientists might find irrelevant a taxonomy grouped by colour hue, while designers might consider it an essential starting point.
- Scientists may be more rigorous than designers when it comes to following the guiding points suggested to navigate the StrC. Some designers may completely ignore these guiding points.
- Collected keywords searched by scientists and designers reveal patterns of coincidence and disparity in the language used to find similar or same results.
- The number of interactions and the time spent navigating sections and features with predominantly scientific content suggests signs of engagement from scientists, while it reveals some limitations for designers in understanding such content.
- The number of discrepancies and conflicts highlighted by scientists from content and concepts included in the StrC contrasts with the number and kind of comments that designers make on the same content and concepts. This may support the idea that a communication gap exists due to different disciplinary languages, ways of knowing, and perspectives. If these numbers and preferences show no big differences across participants from both groups, this may suggest a need to reframe the idea of the "gap,"

and introduce new questions to get at why the biomimetics of structural colour has not yet evolved to design implementation.

- The order of steps used by designers exploring the main StrC features versus the order scientists use may reveal some patterns that characterize different ways of observing, understanding, and engaging with the subject of structural colour.

These points are fully contrasted and compared to findings in Chapter 5.

4.5 The Prototype

From the beginning of the process, even before this definition was settled, the creation of the StrC interface was conceived as *a rich-prospect browsing probe for academic prototyping*. The most influential source to inspire the design ideas of the prototype and its use as a method came from the work led by Dr. Stanley Ruecker, Professor of Design at the University of Illinois, Urbana-Champaign, and former Professor in Humanities Computing at the University of Alberta.

The process of making a real prototype was possible due to the contributions from a team of professors and students in the Department of Computing Science at the University of Alberta (U of A). In 2016, the StrC (back then known as “DTSC”) was a group assignment for the course CMPUT401. A Project Specification Template containing information about the project background, targeted audiences, specific components, technical aspects, and future stages in the development was provided to the team of students. A U of A systems analyst from the Arts Resource Centre (ARC), Omar Rodrigues-Arenas, provided additional recommendations for the future deployment and administration of the prototype.

In addition to technical advice and support received at the initial stages of the prototype development, the scientific advisor to this project, Dr. Tomislav Terzin, and a team of science students from U of A Augustana Campus provided scientific input and support populating and curating the database with specimens from Dr. Terzin's and the Natural History Museum of London's (NHM) collections.

The experience of creating the current StrC prototype (https://strc.online) involved three stages, the design, the development, and the deployment, described as follows.

4.5.1 Design

The design of the StrC interface was influenced by data visualization research projects, done in the digital humanities and humanities computing areas, of which I was a part between 2006 and 2012 at the U of A. Within the same period, I was teaching the subject of information design in the design studies program at Grant MacEwan University reinforced and informed what would be the initial building blocks of this scholarship and the realization of the importance of the creation of such tools for research. These experiences enabled me to collect knowledge and develop the capacity to design solutions to simplify data complexity and facilitate research. The idea of a taxonomic interface was present in several rich-prospect browsing projects designed in those years. The inclusion of data visualization widgets in the StrC environment is directly linked to similar design reasoning present in past projects. For instance, the "sunword" included in the "homology" widget to collect the number of biological orders grouped by colour was originally thought of as a text analysis tool to visualize repetitions on a text or collection of texts,[70] and later adapted to collect Wiki contributions.[71] The "phylogeny" and "evolutionary

[70] "Sunword" was created in 2008 as part of the *NORA-MONK Project of Interface Design and Text Visualizations for Humanities*, funded by the Andrew W. Mellon Foundation, in a partnership of institutions: University of Alberta; University of Illinois, Urbana-Champaign; University of Maryland, College Park; McMaster University; University of Nebraska; The National Center for Supercomputing Applications, Northwestern University.
[71] Sunword was also adapted for the "Visualizing Relative Wiki Contributions" project, conducted by Arazy et al. (2010).

disruptions" widget timelines are inspired by the work on representing non-linear time in text collections.[72]

Auditing the entomology course ENT 527 in the process of creating the StrC concept (DTSC at that time), resulted in a significant influence, too. The sole need to make sense of the complexity of life, its classification, nomenclature, and overall logic of taxonomic thinking described by de Hoog (1981) as a science, grew out of attempts to visualize such a process. This series of first attempts was named "Taxo-Phylo" and converged to an epiphany phase during the review of an anthropologic field work done by Bruno Latour (described in Chapter 3.5.4), which includes the description of the "pedocompactor" (Latour, 1999) as a visual metaphor for data translated into images and imagery becoming data. This "artefact" created by hand and representing a whole collection, connects the concept of rich prospect browsing with the concept of taxonomic research. This tipping point in the conception of the StrC was derived in a first design program and mock-up version developed in Adobe XD (Fig. 4.03), which was used as a preliminary prototype for exploratory purposes. This mock-up version was shared with key scientists involved in structural colour research (biophotonics) during the Living Light conference held at the Scripps Research Institute of the University of California, San Diego in 2016. Conversations with these scientists suggested that developing a research tool such as the StrC would be of great benefit to disseminate and share knowledge on the subject, with special emphasis on the implementation in design innovation.

The design process consolidated after that tipping point and several iterations during independent study courses (HECOL501 and HECOL651), from which the project evolved into

[72] "Timelines" was a series of visualization tools created for the *Implementing New Knowledge Environments* (INKE) project, funded by the Social Sciences and Humanities Research Council (SSHRC) in 2011.

an integrated ecosystem of tools (Fig. 4.04) and later developed as the interface used in the study for this dissertation.

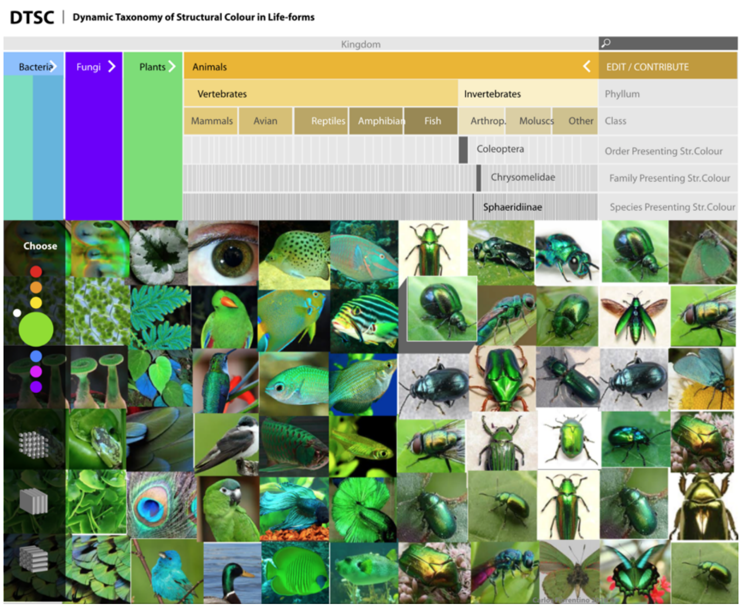


Figure 4.03. Mock-up version of the DTSC interface in Adobe XD.

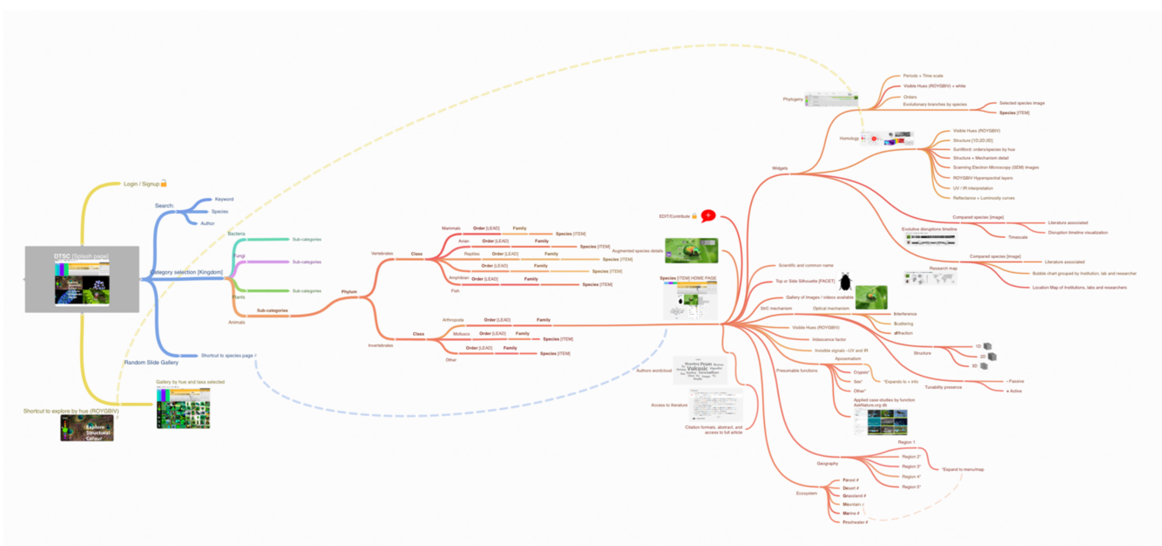


Figure 4.04. Flow diagram of the whole StrC ecosystem planned before development.

4.5.2 Development

The development and management of such digital ecosystem and its functional components (a front-end interface, a database, an administration back-end interface, a project management and collaboration repository, server, etc.), demanded expertise in computing science (programmers, developers). In addition, these contributors might find the subject (structural colour, biomimetic design, science) interesting and motivating.

Dr. Eleni Stroulia (Computing Science, University of Alberta) manifested her interest in supporting this research project by including the development of the StrC interface as a class project for one of the senior courses in Computing Science (CMPUT401). As a requirement to formally offer this project as a choice for a CMPUT401 group assignment, a Project Specification Template was submitted (Appendix 7.2.6). I presented a brief lecture on structural colour to the CMPUT401 class, and the project was later assigned to a group of five students led by Prof. Victor Guana and teaching assistant Diego Serrano. In addition to this support, a U of A systems analyst from ARC, Omar Rodrigues-Arenas provided additional recommendations included in the project specifications delivered to the class.

The team of students from CMPUT401 developed the architecture for the database, the administrative back end, and the front-end interface (Appendix 7.2.6). Students interacted with me through regular meetings held throughout the fall semester of 2017. The deployment of this first version was presented as a formal project submission to CMPUT401 at the end of 2017.

The initial dataset to populate this first version was quite small (about 20 species). By the end of the class project and for the purpose of better showcasing the prototype, students added some more species to get around 100 cases in the collection. In the months after the CMPUT401 class project was delivered, two science students, chosen from the U of A Augustana campus and supervised by Dr. Terzin, contributed to the populating of the database with more species from Dr. Terzin's entomology collection and a selection of species from the Natural History Museum's entomology collection in London. By the time the StrC was ready for the study, the database contained about 240 species that had been manually inputted. It is important to clarify that this mechanism of manually contributing to the database was only designed for an initial dataset. The continuation of the StrC demands further automatization to access external data repositories like the ones listed in Section 4.2.

In addition to Dr. Terzin's contributions to the database, the StrC project has been of interest to other data repositories listed earlier in this chapter, among them the U of A's E. H. Strickland Museum's online entomology collection directed by Dr. Felix Sperling. Support for the StrC also includes the biomimicry case-study-based portal AskNature.org, and the nature-inspired network tool 7Vortex.com. These options can also be accessed from the StrC to retrieve additional information on structural colour and biomimicry.

The final stage of the StrC development required the work of two professional computing developers, experts in the area of integral applications. They moved the entire database and interface components to a new domain and server to make administration more convenient for the researchers. The developers fixed a number of issues and incomplete details from the original programming, and tuned up and finished the main components of the interface used for the study, including initial demo versions of the widgets.

4.5.3 Deployment

The developers deployed a complete version of the StrC interface (https://strc.online) by the end of December 2018. This deployment included access for participants to protocol steps of the study (information sheet, consent form, and guidelines to navigate the StrC), full access to all the components of the front-end interface (website), access to the survey online (Appendix 7.1.7), and access for the researchers to the administrative back-end interface and data collection and data analysis tools (Appendices 7.2.8 and 7.2.9). Appendix 7.2.6 shows the timeline and planning of the steps for developing and deploying the prototype.

4.6 The Study

The StrC study was designed to collect information about and feedback and contributions from participants' interactions with the StrC interface. This material was gathered via responses to a questionnaire about the StrC experience, and interviews with a selection of scientists. The resulting data provided elements for analysis and evidence that support some assumptions and challenge others.

4.6.1 Preliminary Measures

In order to run the study, it was necessary to work with the developers on completing essential functions of the StrC interface, such as the main taxonomy, the search engine, and the components of the species profile pages, with many iterations for design adjustments. The development of the widgets was also a pressing matter given the time frame to complete the study. It was decided to include only simulated versions (neither completely interactive nor using real data) at the time of the study, to test only the potential of these features for further development.

Restructuring and improving the application programming interface (API) in the administrative back-end was also a major requirement for the successful planning use of the interface. A well-organized API backend facilitates the researchers' work; the collection and management of data for further analysis; and the possibility of adding, removing or editing any content of the interface in real time. It also provides options to share access with other researchers. The StrC API was accessed and used by Dr. Terzin and students from the Faculty of Science to populate the database with entomology specimens.

Populating the database manually with new specimens and finishing details of previously entered specimens was a time-consuming task. As stated earlier, the manual work was planned only for the purpose of running the prototype for this study. After about 240 species had been entered in the collection, the StrC interface was ready for the study.

4.6.2 Planning and Execution

The study design involved preparing a series of documents and forms to support and execute the plan: a study protocol describing all the steps and components (Appendix 7.1.2); recruitment materials (i.e., letters of invitation, poster, and media posting; Appendices 7.1.8, 7.1.9, 7.1.10); information sheet, consent form, and guidelines for participants (Appendices 7.1.3, 7.1.4, 7.1.5); a survey with questionnaires for participants (Appendix 7.1.7); and the organization of all these materials to make them accessible online.

In order to get approval to execute the study, a proposal was prepared and submitted to the U of A Research Ethics Office (REO). The REO approved the proposal after several revisions (Appendix 7.1.1). These revisions were mainly focused on issues of confidentiality, given the implications of using third-party research tools (i.e., Google Forms and Google Analytics). These points were properly addressed, and with the approval the study was ready to be scheduled.

Before scheduling the invitation to participants and opening access to the study online, a pre-study test and check point was run to detect any problems or malfunctions of the materials uploaded online, as well as the quality of the content and the mechanisms for data collection and tools for analytics. For this stage, supervisors and advisors to the StrC project, as well as a few of the researcher's colleagues (seven people in total) were informally invited to participate and provide feedback.

After minor adjustments to the pre-study test, the study was ready for execution. It is important to point out that the *academic propototyping* and *digital probing* characteristics of the tool tested implied that many details would be able to be changed during the study, as this prototype was an adaptive work-in-progress rather than a final version.

The steps to formally initiate the study were:

1. Contacting targeted individual participants and participants' groups of interest by email, and posting an advertising poster on social media.
2. Collecting consent and contact information through the StrC study access form.
3. Tracking the activity of the StrC interface through Google Analytics (GA) React tools.[73]
4. Monitoring the collection of feedback through the API, the survey (Google Forms), and analytics tools (GA).

After 8 weeks of collecting data from the activity of the StrC visitors and responses to the survey, the study was closed to initiate a final stage of data analysis and writing conclusions. The StrC interface remained open and activity tracking available for long-term analytics similar to any website; however, that data was not collected and analyzed for this study. Comments provided by scientist participants revealed an opportunity to continue further discussions, guided by questions anticipated in Section 4.3. To address these discussions, a semi-structured interview format (Bernard, 1995) was used, which included a few more questions for a selection of scientist participants. These selected scientists were contacted by email and given a 2-week time frame in which to respond. Collected responses were included in the data analysis. A brief

[73] React, also known as React.js or ReactJS, is a JavaScript library for building user interfaces like the StrC. React Google Analytics Module is a module that can be used to include Google Analytics tracking code in a website or app that uses React for its front-end codebase.

amendment with a few extra documents to conduct these interviews was submitted to and approved by the U of A REO.

4.7 Targeted Study Participants

The study conducted for the StrC involved participants classified in three different areas: participants from science, from design, and from the biomimicry community with another of no specific background but with an interest in biomimetic design.

4.7.1 Participants From Science: Scientists and Advanced Science Students

Participants with a scientific background were targeted, focusing on those in the areas of biological sciences (entomology, botany, zoology, microbiology, evolutionary biology), photonics (physics), and biophotonics (the closest related scientific area to structural colour that involves both physics and biology).

The recruitment process consisted of sending email invitations to access the study, and was mainly focused on inviting scientists from the biophotonics community—those attending the Living Light conference, and those in biophotonic labs from several universities (University of Cambridge, Ghent University, University of Akron, Yale University, among others)—and scientists from the biomimicry global network.

The objective of this category of participants was to observe the StrC as a tool of scientific research, scientific cross-collaboration, and scientific contribution to other disciplines interested in structural colour (such as design disciplines).

4.7.2 Participants From Design: Designers and Advanced Design Students Interested in Biomimetic Design

Participants with design backgrounds were strategically targeted (industrial, visual communication, architecture, fashion, interior, engineering, etc.). The recruitment process consisted of sending email invitations to access the study, and was mainly focused on inviting professionals, researchers, and students (graduate and advanced undergraduate) from all areas of design considered, with a specific interest in applying biomimicry, and in some cases specifically structural colour. Most of these participants were contacted through the biomimicry global network, biomimicry local and regional networks, design programs with biomimetic design areas of study, biomimetic design labs, and biomimetic innovation hubs across the world.

The objective of this category of participants was to observe the StrC as a source of information for design research on structural colour, and as a tool for collaboration for biomimetic design projects on structural colour.

4.7.3 Other: Non-Design and Non-Sciences Participants Interested in Biomimetic Design

Participants with neither a scientific nor a design background, although interested or already involved in biomimetic design projects, were included in the study under this third category. This category included professionals from multiple disciplines (e.g., anthropology, education, fine arts, etc.). These participants were also contacted by email to access the study, or through the biomimicry global network, and biomimicry local and regional social media networks.

The objective of this category of participants was similar to the designers' category; however, there were different expectations in terms of the kind of responses this group might produce, given their limitations of knowledge about design and/or science subjects. For the purpose of data collection and analysis, these participants were merged with designer participants under the category "designers+."

4.7.4 Sequence of Recruitment and Participation Process

The recruitment process for all study participants consisted of the following steps:

- Step 1. Contacting targeted participants by email individually or through mailing lists.

This invitation included the links to access the study (http://strc.online/study) and the survey (http://strc.online/survey), and attachments of a poster (Appendix 7.1.9), guidelines (Appendix 7.1.5), and information sheet (Appendix 7.1.4).

- Step 1 Contingency. When targeted participants did not respond after 2 weeks had passed after the original invitation was distributed, a reminder (with content similar to that in the original invitation) was sent.
- Step 2. Participants accessing the study had access to the researchers' contact information, the information sheet, and the consent form. Once the consent form was completed and participation agreed to, they could continue to access the StrC interface.
- Step 3. When participants accessed the study (Google Forms), the researcher received an automatic notice by email, and a copy of the consent form; the participant received an automatic confirmation, message of acknowledgment, and a reminder to proceed to complete the survey.
- Step 4. When participants completed the survey (Google Forms), the researcher received an automatic notice by email and the survey results; the participant received an automatic confirmation and message of acknowledgment.
- Step 4 Contingency. When the participant only accessed the study but did not complete the survey, the researcher sent an email reminder to complete the survey.

While this general procedure (Fig. 4.05) made it possible to obtain a significant portion of the responses, other collateral situations also helped to recruit participants from all areas, e. g., promoting access to the StrC in conferences and lectures given by the researcher between January and March 2019, or the researcher's personal contact with scientists and designers willing to participate in the study.

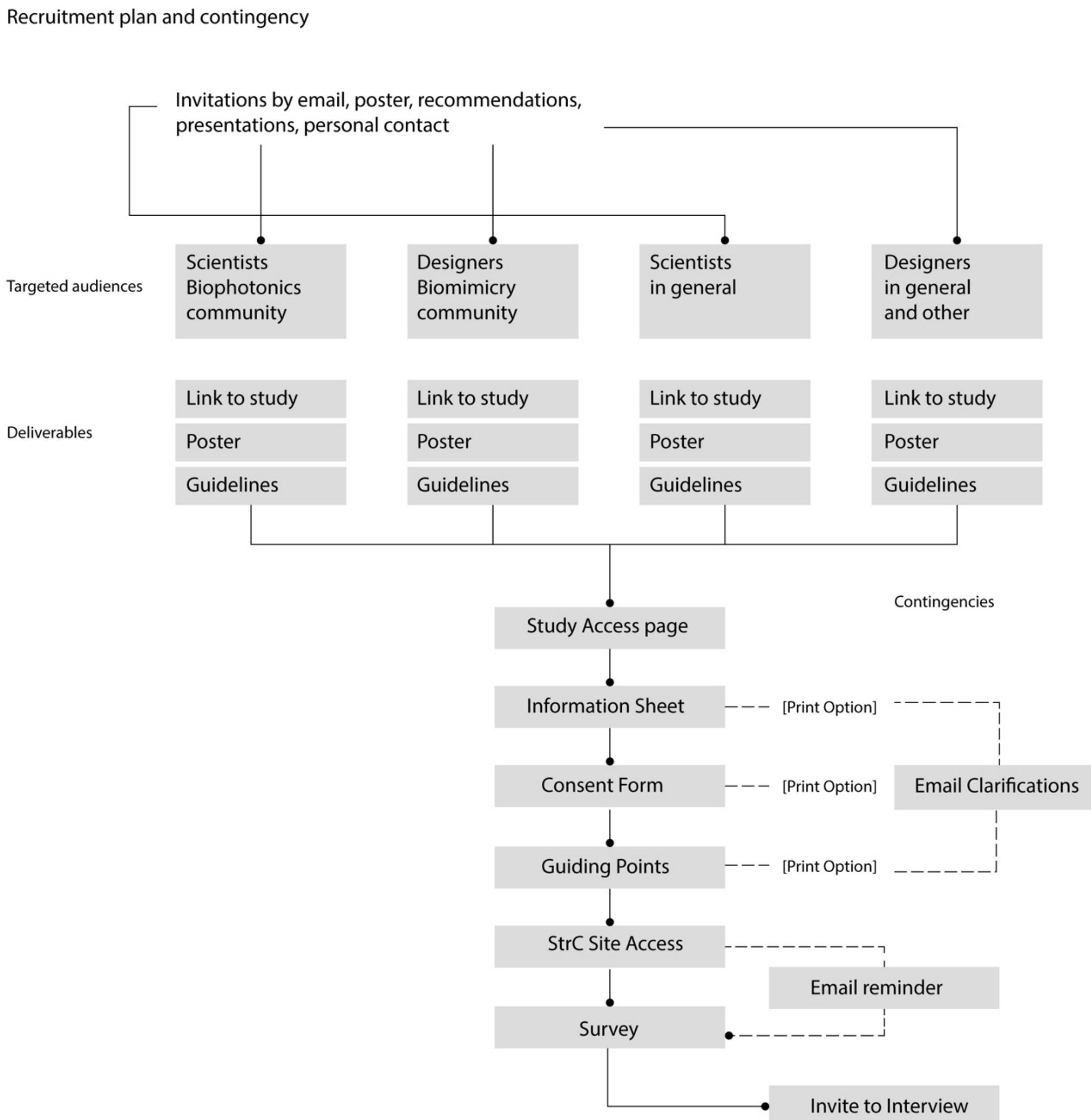


Figure 4.05. Sequence of recruitment steps for all study participants.

4.7.5 Demographics Collected From All Survey Participants

The study collected data from 61 visits to the StrC interface and 19 participants responding to the survey during an 8-week period. Section 1 of the survey asked all participants basic demographic questions before and after accessing the main questionnaires. Scientists, designers, and biomimetic practitioners from eleven countries (detailed in Chapter 5.1.1) and 15 research institutions and companies (listed on p. 132), from a multidisciplinary spectrum (listed on p. 130), all interested in structural colour and biomimetic design, constituted the critical mass source of this study. Demographic data from participants served as contextual data, and helped to clarify the diversity of experience, fields, and locations across the sample. It also helped to determine the selection and planning of email interviewees.

The first question of Section 1 also served to determine disciplinary backgrounds, and redirect participants to the appropriate section of the survey (Section 2.1 for scientists, Section 2.2 for designers and other practitioners). The rest of the demographic questions came at the end of the survey (after participants had responded to the main questionnaires) to identify the level of experience in the fields, level of literacy in biomimicry and structural colour subjects, and affiliations and geolocations. This demographic data served to set the context for the qualitative analysis derived from Section 2 of the survey (details in Chapter 5). What follows is a summary of this collected information.

4.7.5.1 Scientists, Designers, and Other Practitioners

Eleven participant scientists were redirected to fill out the questionnaire in Section 2.1 of the survey. They represent 58% of the sample. The remaining eight participants consisted of designers and other practitioners interested in biomimicry. They were redirected to Section 2.2 and represent 42% of the sample (Fig. 4.06).

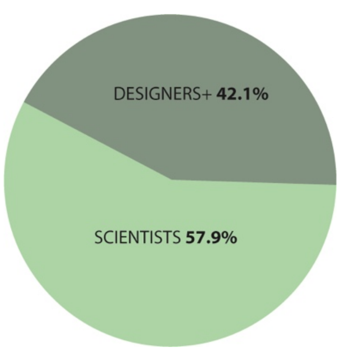


Figure 4.06. Distribution of participants collected by Google Forms. The two main groups were redirected to Sections 2.1 and 2.2 of the survey.

Seven more demographic questions on disciplinary areas, experience, education, affiliation, and level of knowledge on the matters of the study were asked after participants had completed the main questionnaires in Section 2 of the survey.

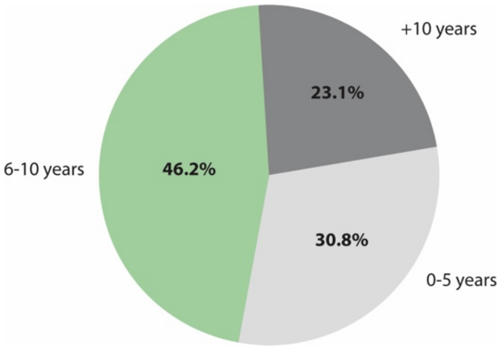
4.7.5.2 Experienced and Educated Participants romF Diverse Disciplinary Areas

From the two groups differentiated for Sections 2.1 and 2.2 of the survey, a variety of disciplinary areas were represented in the sample:

- Section 2.1
  - Biophotonics (Natural photonics, biology + physics + optics)
  - Entomology
  - Evolutionary genetics
- Section 2.2
  - Biomimetic visual communication design
  - Biomimicry systems (Ecosystems)
  - Education
  - Landscape architecture
  - Data science
  - User experience design
  - Visual communication design

Within this rich spectrum of disciplinary areas, 14 participants (74%) were scholars/researchers, five (26%) were professional practitioners, and four (21%) were graduate students (note that some participants applied to more than one category). This sample implies a highly trained and educated audience evenly distributed in degree levels achieved: bachelor's (31%), master's (31%), and PhD (38%). See Fig. 4.08.

The majority of these participants were also experienced (23%) or very experienced (46%) in their areas of study (Fig. 4.07).



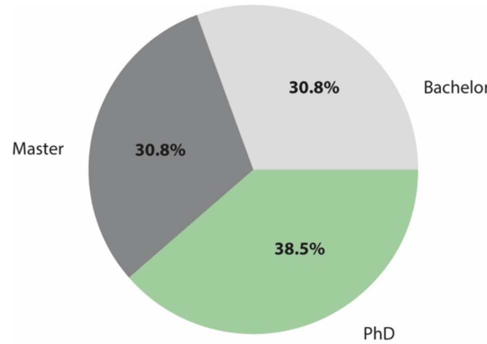


Figure 4.07. (Left) Distribution of participants by years of experience in their areas. *Figure 4.08*. (Right) Distribution of participants by highest education degree achieved.

4.7.5.3 Affiliation

Corresponding with the number of scholars, researchers, and students among the participants, most participants (69%) choose "university/college" as their main affiliation, with the remainder (31%) affiliated with companies. No independent professional participated in the survey (Fig. 4.09).

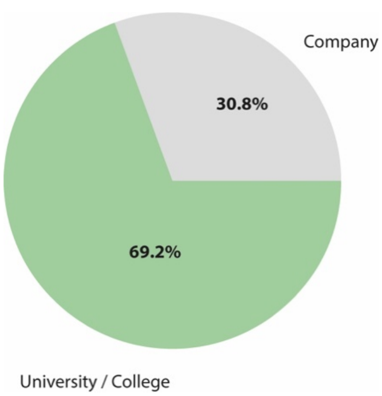


Figure 4.09. Distribution of participants by affiliation.

Consistent with the previous demographic distribution details, most affiliations were education and research institutions (twelve in total). There were also three participants affiliated to companies. The geographic diversity can also be observed from Google Analytics (GA) demographics distribution by country in Chapter 5.1.1. The diversity of institutions and countries not only enriched the results, but offered a sense of the global distribution of main research environments for the subject of biophotonics. In the long term, it will be possible to see this distribution and a full review of all researchers, research teams, labs, and institutions by using the StrC. In the future, once the 7Vortex research map widget is developed, the information will be accessible through that portal.

The following is the list of institutions, areas, and locations collected from participants:

- 7VORTEX; CEO, Genval, Belgium
- Arizona State University, The Design School, Phoenix, AZ, USA
- EY, n/a, London, UK
- Hobart and William Smith College, n/a, Geneva, NY, USA
- IBI Group, Landscape Architecture, Edmonton, Alberta, Canada
- UC Berkeley, n/a, Berkeley, California, USA
- UC San Diego, Scripps Institution of Oceanography, San Diego, California, USA
- University of Alberta, Faculty of Art and Design, Edmonton, Alberta, Canada
- University of Alberta, Department of Biological Sciences, Edmonton, Alberta, Canada
- University of Cambridge, Department of Chemistry, Cambridge, UK
- University of Exeter, School of Physics, Exeter, UK
- University of Ghent, Department of Biology, Ghent, Belgium
- University of Namur, School of Physics, Namur, Belgium
- University of Sheffield, Department of Physics, Sheffield, UK
- Virginia Tech, Entomology, Blacksburg, USA

4.7.5.4 Knowledge of Biomimicry/Biomimetic Design, Biophotonics, and/or Structural Colour Physics

Participants were given options to choose, rating their knowledge from “high” to “none.”

Overall, knowledge of biomimicry was evenly distributed across all participants, with most considering themselves knowledgeable or very knowledgeable, while the remaining were more cautious or admitted not being knowledgeable about the subject. A similar proportion of scientists and designers considered themselves highly knowledgeable; however, scientists predominantly admitted to knowing less than designers about biomimicry (Fig. 4.10).

Participants were more polarized in their knowledge about biophotonics, although cases were still distributed from very knowledgeable to not knowledgeable at all. As expected, the results clearly show that scientists were the most knowledgeable while designers and other discipline practitioners were less knowledgeable (Fig. 4.11).

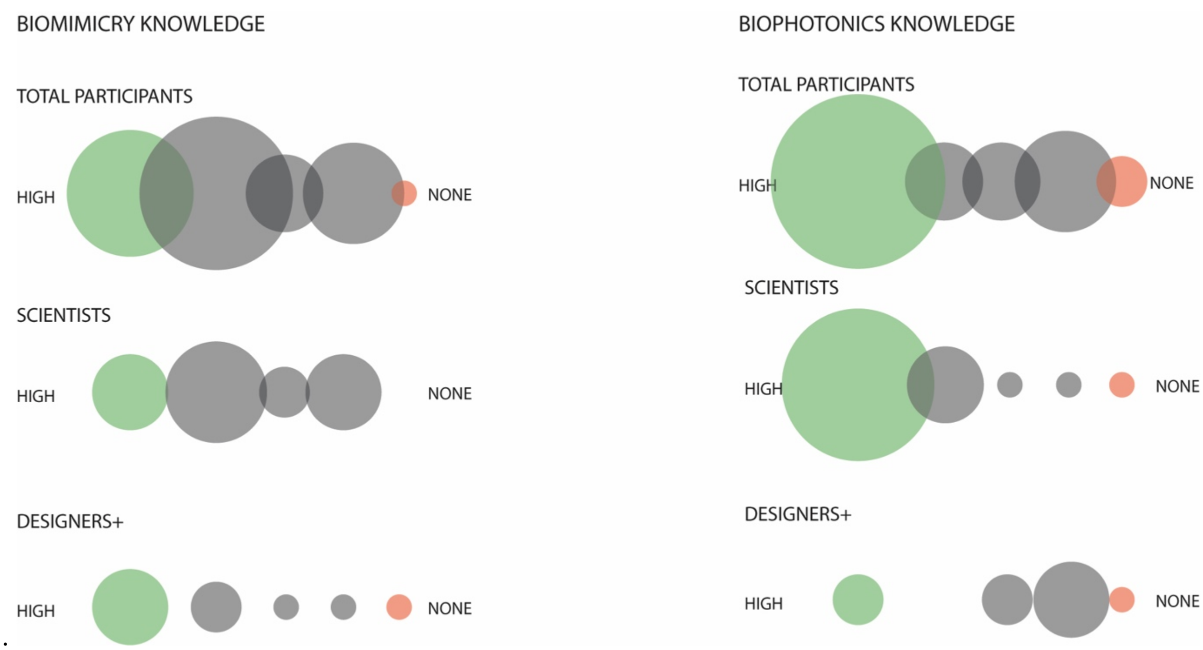


Figure 4.10. (Right) Participants' level of knowledge on biomimicry. *Figure 4.11*. (Left). Participants' level of knowledge on biophotonics. These bubble visualizations are separated in the two main categories, "scientists" and "designers+" (design and other disciplines). The size of every bubble represent the number of participants choosing the options ranking from "high" (green) to "none" (red). The grey bubbles indicate neutral or closer to neutral positions.

4.8 Data Collection

The data collection process was planned to obtain contributions from study participants in four ways (Fig. 4.12): (a) reading the activity of participants accessing and testing the rich-prospect interface (GA, Google React Analytics tools); (b) collecting feedback through the *red layer* to the back-end of the interface (API, Application Program Interface); (c) questioning through a self-administered survey (Google Forms); and (d) asking a selection of participants (specifically from targeted scientists) a few additional questions in a brief, semi-structured interview (by email exchange).

The first two ways (reading analytics from participants' experiences and a built-in function for collecting feedback) are inherent in the interface. The other two ways were added to obtain qualitative data and address the limitations of an "uncontrolled" academic prototyping experiment, which can lead to inconsistent results. These limitations are not uncommon in cultural probes (explained in Chapter 3), and require additional methods to collect reliable data (Gaver et al., 1999).

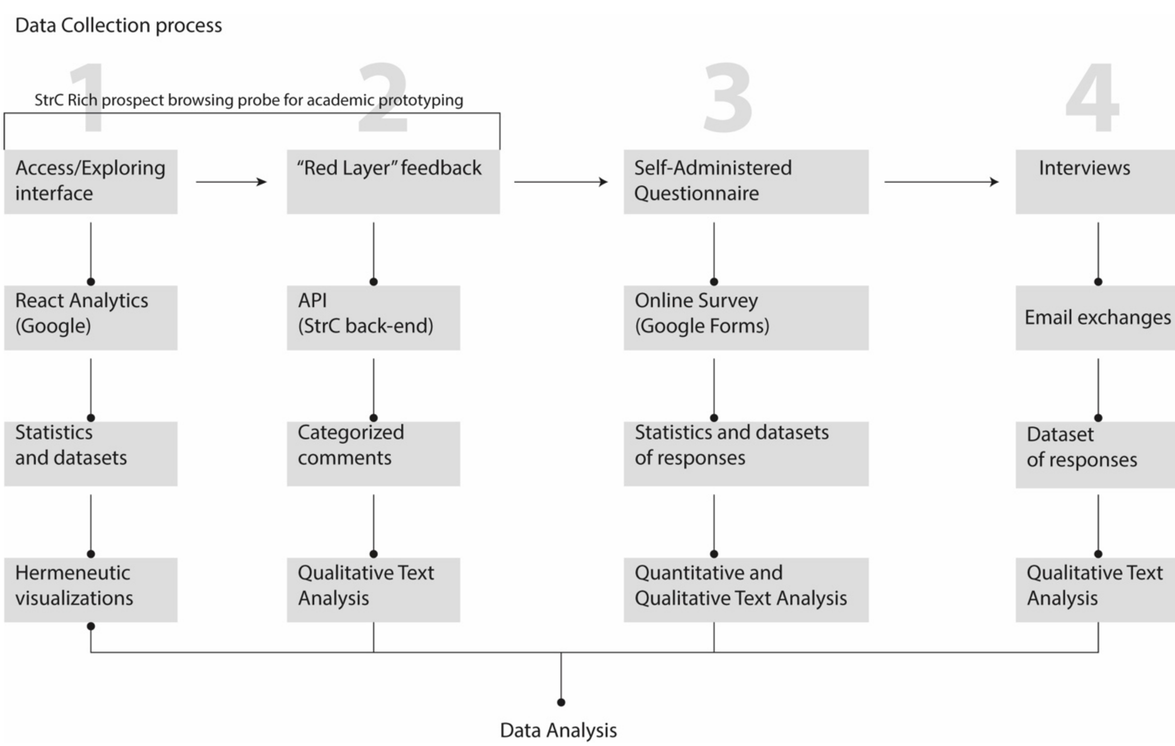


Figure 4.12. The four ways of collecting data.

4.8.1 Exploring the Rich-Prospect Interface

The StrC study involved testing the rich-prospect browsing ecosystem (the StrC prototype, described in Chapter 3.3, 3.4, and in more detail in Chapter 4.5) as a digital informational probe (as described in Chapter 3.5.1) for an academic prototyping exploratory research purpose. The multiple-method characteristic and multi-dimensional methodological approach to the study brings a variety of data formats and outcomes as a consequence of the synergies created by the combination of techniques and methods applied. The digital nature of the StrC ecosystem made accessing and sharing it relatively simple for the study participants. The targeted participants accessed the StrC interface during an 8-week period, guided by preassigned tasks listed in the guiding points list (Appendix 7.1.5), which served to facilitate the participants' experience as a semi-structured exploration. Their interactions and contributions were collected for analysis. The StrC interface was connected to React-GA Analytics, which made it possible to track the page views, duration of visits, events triggered, terms searched, et cetera. The interaction alone of participants with the StrC interface and its functions can generate statistical data *per se* (e.g., quantitative indicators of frequency, number of repetitions) that can be translated into indicators like pattern recognition and hermeneutic interpretations typically used in content or text analysis tools. The results were grouped according to the category of participants and the subsequent interactions between each participant and the interface, sections visited, words searched, et cetera.

4.8.2 Collecting Feedback Through the Red Layer Feature

One key feature of the StrC interface was the red layer activated from the "Edit/Contribute" button on the main menu. This layer contains "hot spots" assigned to specific functions of the taxonomy page, the species profile page, and the widgets. Through this layer, the participants could contribute by sending endorsements, suggestions, corrections, and additions; and by asking questions; noting conflicts; and adding files, links, and an email address where they could be contacted (Fig. 4.13a, b, c). This input helped, in an academic-prototyping fashion, to improve the content of the interface while the study was conducted. A list of issues addressed by collecting input is detailed in Chapter 5.

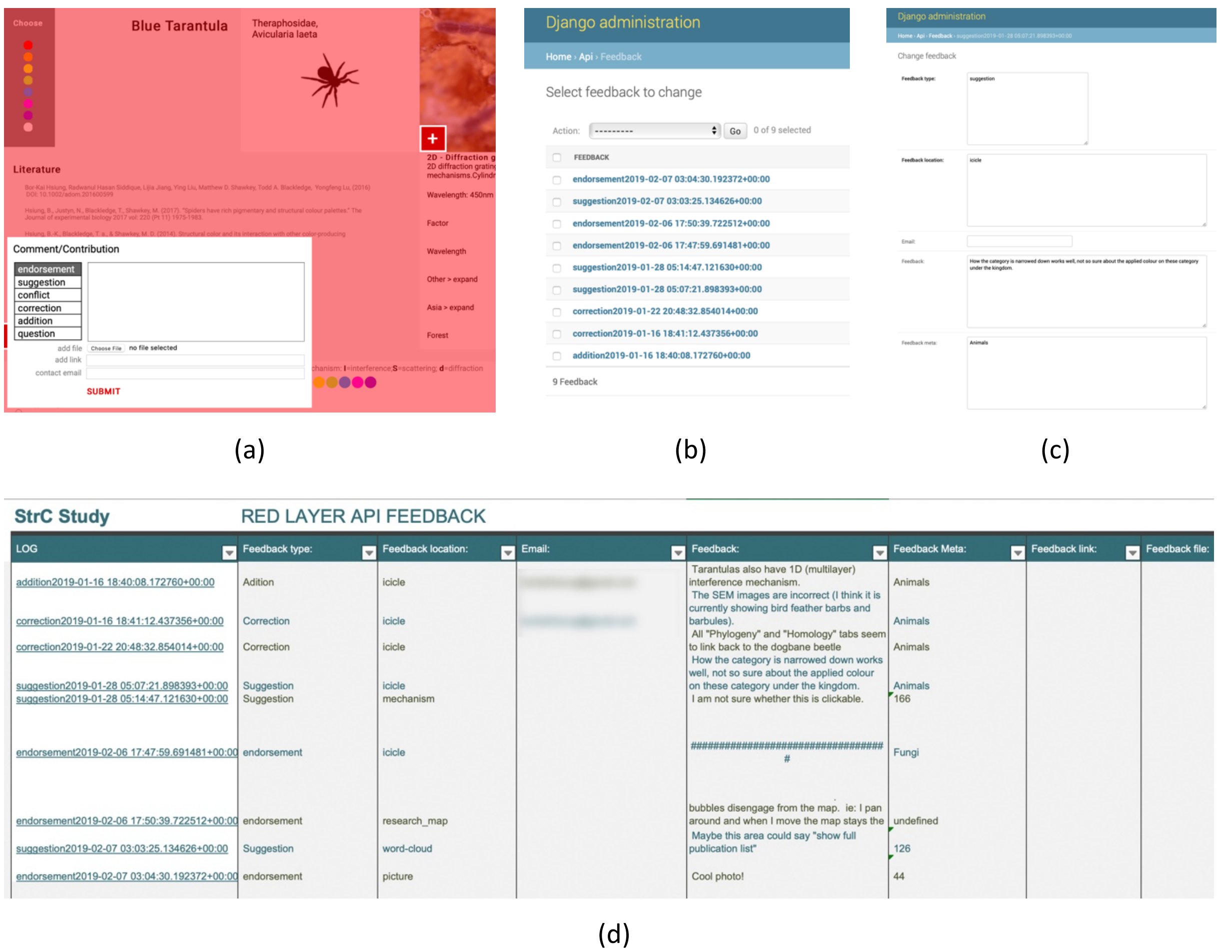


Figure 4.13. (a) Red layer hot spots and activated feedback forms in the StrC; (b) Feedback logs collected by API; (c) Categorized feedback available from the back end; d) Follow-up spreadsheet.

4.8.3 Questioning Through a Self-Administered Survey

In addition to collecting data from the interaction of participants with the prototype, and with the intention to enrich the study with qualitative data, participants were asked to fill out an on-line, self-administered questionnaire (Appendix 7.1.7). There were key-guided questions regarding the StrC functionality and potential use, and related subquestions. Most questions offered space for additional comments (open-ended questions) in order to collect responses more susceptible to qualitative analysis. There were two versions of the questionnaire, one for scientists (12 questions) and one for designers and other biomimetic practitioners (10 questions).

Surveys are more effective than interviews when three conditions are met: (a) the researcher deals with literate respondents, (b) a high response rate is possible, and (c) because of the nature of the questions, face-to-face responses are not required (Bernard, 1995). Self-administered questionnaires have advantages and limitations (Bernard, 1995). The advantages of the StrC survey design can be summarized as follows:

- It allowed a single researcher to gather data from a relatively large sample of respondents at a low cost and with logistical ease.
- Questions were consistently asked throughout the sample, with no interviewer bias.
- More complex questions could be asked than in personal interviews, with the possibility for the respondents to reflect longer on the answers.
- A series of related (and/or necessarily repetitive) questions could be asked with low risk of losing the respondent's attention.
- Anonymity gives people a sense of security, and allows more inhibited responses.

There was only one design disadvantage identified: there is always a risk of misinterpretation that can lead to answering a question incorrectly or not representing what the respondent intended to say. This happened in a couple of cases where the comments were misplaced. However, once these were identified, it did not affect the overall results and findings.

The kind of questions included were closed-ended questions such as "Would you be interested in contributing with scientific data to the StrC database?" (see Chapter 5, Q2.1.3) and open-ended questions such as "Please provide additional feedback, comments and suggestions about the design and content of the following StrC features" (see Chapter 5, Q2.1.12). The open-ended questions were designed to get additional thoughts from the participants. Closed-ended questions, while intimidating if they are sensitive, are more efficient in getting accurate and unbiased responses. Open-ended questions produce less clear answers but seem less intimidating for adding additional thoughts and opinions (Bernard, 1995). When both kinds are included, the proportion may favour more closed-ended than open-ended questions. Following this criteria, the StrC study contained main closed-ended questions and open-ended questions proportionally. Open-ended questions collected complementary comments to the main closed-ended questions. The study questionnaires also used the concept of packaged questions (Bernard, 1995) to organize the content in multiple-choice, scale type, and ranking options. For instance, there was a question, "What other data visualization tools would you like to see in the StrC environment?" with five checkbox options plus an "other" option (see Chapter 5, Q2.1.6). Other questions included "The taxonomic content of the StrC (levels, categories and items) is correctly organized" with a five-point scale from Agree to Disagree (see Chapter 5, Q2.1.2), and "Rank how the widgets would serve best to speculate with existing and/or new theories and hypothesis" with a multiple choice grid with four options (see Chapter 5, Q2.1.10).

In addition to these strategies, before the study was unveiled, there was a trial run with a contingency plan. The contingency plan had possible combinations of responses to prevent unclear points or inconsistencies that had the potential to affect the data analysis. Thus, the grouping and order of the questions were carefully planned for improving the response rates, following recommendations inspired in the "Don Dillman's Total Design Method" (Bernard, 1995, p. 277). Taking into consideration all these factors facilitated an efficient and effective collecting process that fed the data analysis in volume and quality.

Data collected as text format was also used for hermeneutic visualizations (used in Chapter 5) and visual pattern recognitions (method described in Chapter 3.5.2).

4.8.4 Collecting Additional Thoughts From Scientists (Semi-Structured Interviews)

After scientists explored and interacted with the StrC, they provided valuable feedback and interesting new elements for discussion. This dynamic is an essential characteristic anticipated in the research question, the role of the StrC as a research tool to bridge intra- and interdisciplinary gaps. The quality of responses to the survey was enough for measuring the StrC effectiveness. Comments collected from the survey (such as the following) were consistent to results collected across the study: "*…the platform* [is] *accessible to not just specialists in the field but to all researchers*" (response to question 2.2.3 of the survey). Findings in Chapter 5 bring more evidence of this. Some points highlighted by scientists may inform the future steps of the academic prototyping process of the StrC. Some of these points however, suggested that a few more questions might be worth asking before arriving at final conclusions from the data analysis. For this, a brief, semi-structured interview format was designed to be shared by email or internet calls. The content of these interviews is described in Appendix 7.1.11.

According to the data types obtained, the study provides evidence of three overarching goals as subjects of analysis: (a) The level of scientists' interest in exploring and contributing to the StrC; (b) The level of interest of biomimetic design practitioners and researchers in exploring the StrC and the subject of structural colour, following a "biology to design" biomimicry approach; and (c) The detection of synergies between scientists and professional practitioners and researchers interested in structural colour and biomimetic design, which can be achieved by evaluating commonalities and convergences in the data collected.

4.9 Data Types

There were five types of data involved in this research: (a) data obtained from field notes, (b) statistical/quantitative data from Google Analytics tools, (c) qualitative data obtained from the *red layer* StrC feature; (d) quantitative and qualitative data from the survey/questionnaire responses; and (e) responses to the email interviews.

4.9.1 Field Notes

Field notes were used as a method before, during, and after the study. Preliminary to the study, field notes were taken as a documentation process in preparation for carrying out the StrC experiment; during the study, notes were used as a mediation tool between memory and publication (Jackson, 1990), to account for findings that may have resulted in adjustments to the continuation of the study (e.g., identifying new questions, preparing a short list of survey participants to be contacted for interviews); after the study, notes were used to inform the writings of this dissertation, organizing the data collected for analysis and connecting findings with the initial assumption of interdisciplinary communication gaps stated in the research questions. Field notes are not unfamiliar to designers. In design education the importance of taking notes is often emphasized. Notes serve to collect and produce evidence of a design process that always starts in the mind, becomes tangible in a process sketchbook, and is later transformed into a final design version. In a similar way, this research echoes a design processing.

Alongside notes, quick diagrams, photographs, sketches, and research tables were used while conducting different stages of building the StrC datasets, developing the prototype, and designing the StrC study. Many of these notes and sketches were transformed into part of the designed tools for the study; for example, the idea of a taxonomic browser than later became the StrC interface started as a field note diagram during an entomology class project (see Figure 3.05

in Chapter 3). Foveon (infrared) photography and Scanning Electron Microscopy (SEM) sessions were intended to populate the initial StrC datasets. Taking field notes and photographs and creating drawings and diagrams during these sessions helped to improve the design of the features of the StrC species profiles and widgets. Research tables created during the collection of GA data, the process of monitoring and collecting the surveys, and email interviews helped to keep the "study agenda" organized and the timing for every stage of the study under control. Last but not least, the development of hermeneutic representations of the data collected started as notes taken during the data collection. Field notes were strategic not only as a recording method but also as a way to exercise reflection while practicing research.

4.9.2 Statistic/Quantitative Data From GA Tools

Statistic/quantitative data from GA tools were obtained from the activity of participants accessing and interacting with the StrC interface. In part contextual demographics to complement the surveys, in part a qualitative resource to analyze data from participants, GA data offered details about participants' interests and preferences, and served to identify limitations, behavioral patterns, and opportunities for further research (see Chapter 5.1.1 for details). The GA interface provided lists, tables, and simple charts from data that were later cut down into spreadsheets. These spreadsheets were used to produce further hermeneutic visualizations and inform this dissertation.

4.9.3 Comments Collected Through the Red Layer

Qualitative data obtained from participants' comments entered into the red layer StrC feature was collected by the API as a list of logged entries, and later exported as a spreadsheet (see Fig. 4.13a, b, c). This spreadsheet was used during the study to follow through with the improvement of the academic prototyping process (i.e. adjusting and modifying the StrC interface if needed during the study), and it was taken into account when collecting additional findings not denoted in the survey and interviews. In addition to the content collected, the red layer was also used to test its functionality as a mechanism for collecting, contributing, and sharing scientific information in a peer-reviewed fashion.

4.9.4 Quantitative and Qualitative Data from Responses to Survey/Questionnaires

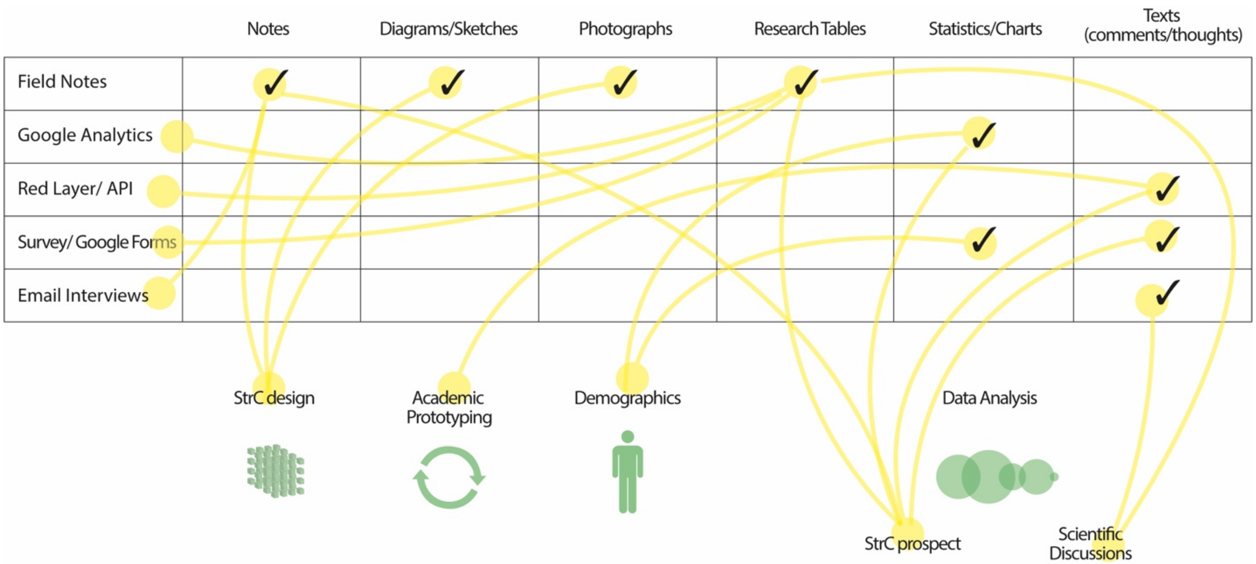
Responses collected through the survey/questionnaires provided some basic quantitative data and fundamental qualitative data from participants. This data was administered and collected from the Google Forms interface. Overall statistics from the total participants were updated in real time during the study, in the form of lists and charts with statistical figures. Details of individual responses from participants were available in form of texts and participants' choices were highlighted in Google Forms responses (e.g., multiple choice, ranking, etc.). Both overall statistics and the summary of individual responses were exported into a unified spreadsheet that was used to produce the hermeneutic visualizations for analysis that also illustrate the findings of this dissertation (Chapter 5).

4.9.4.1 Responses to Interviews

Responses to the four semi-structured questions posed to a selection of scientists in email interviews were collected individually, first as texts and later all organized in a unified spreadsheet. The nature of the questions was strictly scientific and intended to continue the scientific discussions on structural colour that were not reflected in other comments (neither in the survey nor in the red layer comments). These responses helped to complete concepts initiated in the survey and provided better elements for the findings in Chapter 5. Discussions initiated may lead to the development of the StrC features that will facilitate understanding for biomimetic designers. The content of these responses was analyzed qualitatively via text analysis, however no hermeneutic interpretations were needed this time.

Table 4.01

Data Types (Rows) and Data Varieties (Columns) and Their Links to Different Areas of the Study



Collected entries from the study provided qualitative and quantitative data that reflected the study's three overarching goals: (a) Measuring the level of interest of scientists to explore and contribute to the StrC; (b) Measuring the level of interest of professional practitioners and researchers interested in biomimetic design to explore the StrC and the subject of structural colour; and (c) Detecting synergies between scientists and professional practitioners and researchers interested in structural colour and biomimetic design.

4.9.4.2 Qualitative Data

The online surveys and participants' responses from goals (a) and (c) of the study, the latter of which were collected by the StrC red layer feedback feature stored in the administrative back end, are basically rich-text format files to manually feed simple spreadsheets and digital notes, organize them in corresponding digital folders, and store and back them up in restricted cloud servers.

Data were collected as feedback from participants' contributions to the Edit/Contributions red layer of the StrC interface (accessible from the API) and feedback from participants' responses to the Google forms survey questionnaires.

Feedback from participants' contributions using the red layer of the StrC interface were classified as follows:

1. Log entry: provided time, date, and feedback type.
2. Feedback type: provided participants' input classified under endorsements, suggestions, corrections, additions, questions, and conflicts.
3. Feedback location: provided a reference to the StrC function visited—"hot spots" of the red layer (e.g., taxonomy icicle, 1D, 2D ,or 3D mechanisms).
4. Email: allowed the participant to be contacted about the feedback provided if he/she wished.
5. Feedback content: showed the comments typed by the participant under feedback types, similar to open-ended questions.
6. Feedback metadata: provided a reference to the categories and sections visited in the taxonomy (e.g. animals or species numbers).
7. Feedback link: allowed the participant to suggest a website address.
8. Feedback file: allowed the participant to send a file (article, photograph, etc.).

Responses to the self-administered survey questionnaires (Appendix 7.3.1) were divided into three sections: one common section for all participants, one for scientists, and one for designers and other participants (other or not specified disciplines). The questionnaires consisted of a combination of guided and open-ended questions. The common section contained eight demographic questions (with subquestions). The section for scientists contained 12 scientific-oriented questions (with subquestions). The "designers+" section contained 10 design-oriented questions (with subquestions). The quantitative and qualitative information obtained from the questionnaires was used to create hermeneutic representations for text analysis (i.e., word clouds, bubbles, and other charts) and for identifying, grouping, and classifying patterns and for the convergence of ideas (see findings in Chapter 5).

After taking part in the survey, a selection of participant scientists was contacted by email and invited to answer a short (four-question), semi-structured questionnaire about structural colour. The questions focused on identified areas of discussion (Appendix 7.1.11).

4.9.4.3 Quantitative Data

Before the qualitative datasets were collected for text analysis, quantitative data was available from the interaction with the StrC interface. That data was collected through GA React tools as numerical entries represented in spreadsheets and charts, saved by totals as well as broken down by categories and individual items. These numerical entries are quantifications of trackable actions that participants carried out while navigating the interface (e.g., number of log-ins, average duration of sessions, number of pages visited and events clicked (or touched) in the main taxonomy menu page, number and details of species pages explored). This quantitative data was used to provide additional statistical support for the qualitative analysis.

Despite the relatively small sample, the statistical/quantitative data from the GA made it possible to detect navigational trends and patterns in the StrC interface that seem to correlate with the data collected from the comments and responses. The statistics from the GA offered key elements for analysis from behaviour flow indicators, such as number, frequency, and length of events (pages, sections, and widgets of the StrC) visited by participants. They also made it possible to identify which species of the collection the participants visited.

The GA features used to track participants' activity navigating the StrC interface were:

1. Audience Overview. This provided quantitative information on the total number of users, number of returning visitors, number of total sessions, average number of sessions per user, number of page views, average session duration, demographic distribution by geolocation, and browsing and system details. This feature was important to contextualize the participation response to the study.
2. Behaviour Flow. This provided a flow chart visualization organized by different categories/dimensions (e.g., event actions). This feature made it possible to visualize the number of pages accessed and the number of iterations, with session and drop-off details.
3. Top Behavioural Events. This provided the most relevant data from the GA. It made it possible to identify total numbers and individual details of events organized by the five main categories: taxonomy (or "icicle"), widgets, colours (selected with the "colour picker"), search (typed keywords), and feedback (from the red layer). These numbers could be also broken down to event actions (e.g., clicked literature from word cloud widget, individual widgets, individual colours, orders, phyllia, individual species), which provided a way to verify the use of the guiding points provided to the participants, as well as to quantify and distribute participants' preferences.

4.10 Data Analysis

The complexity of an interdisciplinary study demanded a diversity of data types, and a rigorous yet pragmatic plan to follow up, administrate, and deliver the clearest possible results for qualitative analysis. The flexibility that combining multiple methods for data collection offers, helped when dealing with the complexity of the task. This flexibility also helped to cover the two-fold purpose of the survey: providing data content and allowing recruitment for interviews. Several techniques for data management (Denzin & Lincoln, 2008) were practiced in connection to methods mentioned in Chapter 3: writing and notetaking, individual survey analysis, multiple tables for data administration, summarized survey reports, subjective data filtering, storage and backup, and hermeneutic visualization tools (Ball & Smith, 1992).

4.10.1 Writing and Notetaking

Research notes (Emerson et al., 1995) were taken throughout the study and the writing stages of this dissertation (Rapley, 2001). These notes were administered in digital format for rapid access and use, both as digital text documents or photos taken of manuscript notes. Manuscript notes and diagrams were collected in notepads (not on loose sheets of paper). Digital files were stored in a specific notes folder.

4.10.2 Multiple Tables for Data Administration

Managing data to be formatted into tables implies a kind of information filtering and reduction process, where decisions are made to focus on specific tasks or types of data. The spreadsheets listed below were focused on the administration of data obtained for and from the study, to cover specific points to manage different aspects of the study, and to analyze different types of data.

- *Spreadsheet for enrollment follow up (surveys and interviews)*. Before the study began, a Microsoft (MS) Excel spreadsheet was created to follow up on the targeted individual participants and groups contacted for the surveys, and to later contact a selection of participants for the interviews. This spreadsheet was also prepared to classify the demographic information to be collected from the participation in the surveys. The follow-up sections of the spreadsheet listed the number of invitations sent, notes about sending dates, confirmation of invitations received, access to the study, filled surveys, participants contacted for interviews, interview consents collected, and interviews responded.

- *Spreadsheet from Google Analytics*. The GA interface made it possible to download different sections of data collected in the MS Excel file format (e.g., the list of events, time tracking per sessions, geolocation). These tables were not used as final versions of data, but as an intermediate step to create hermeneutic visualizations and other data analysis materials.
- *Spreadsheet from Google Forms (surveys)*. Google Forms also makes it possible to download the data collected from participants to the survey in an MS Excel file format. All the information collected from the surveys (i.e., log time, contact details, responses and comments) could be organized by participant and question numbers and then collected under one unified spreadsheet. This made it possible to use the content for text analysis and hermeneutic visualizations, such as the word clouds and bubble charts used in Chapter 5 to represent findings.
- *Spreadsheet from API Feedback (Red Layer)*. As with Google tools, the API interface made it possible to download as an MS Excel file data collected under "feedback" from entries to the red layer. All the comments were collected under one unified spreadsheet and later used as materials shown in findings.
- *Spreadsheet for interviews administration*. Another spreadsheet was created to collect the responses to the email interviews from the Apple Mail application. Responses were ordered by question number and participant. This table was only used as an intermediate step to analyze the texts.

4.10.3 Individual Participant Analysis

The Google Forms interface made it possible to individually access the responses to the surveys (i.e., to access the responses of individual participants rather than only by question). This made it possible to analyze one survey at the time, and examine details of the different responses made by an individual respondent.

4.10.4 Summarized Survey Reports (Google Forms)

The Google Forms interface also made it possible to access a summary of responses where the results were organized in lists and charts assembled from all of the data collected from all of the participants. This feature permitted the use of some of these charts as figures that reported on the distribution of responses to the survey questions in the findings chapter (Chapter 5), and demographic data described in Section 4.7.5.

4.10.5 Subjective Data Filtering

An important task of the data analysis was to fine-tune the collected responses to identify and eventually eliminate redundancy and irrelevant data. For instance, repeated comments such as “likes” and “dislikes,” while useful as a measure of connotation factors (e.g., general levels of acceptance or rejection), were also irrelevant as qualitative data. These cases were manually filtered from the writings. The repetitions, however, were counted as quantifying data to create text visualizations.

4.10.6 Data Storage and Backup

Data collected digitally was stored on personal Apple Macintosh computers, a backup external drive, and in two different clouds: Google Drive and Adobe Cloud. Every type of data was organized in different folders (e.g., “Interviews,” “API red layer,” “Surveys”) for easy identification and access. The folders were indexed according to the date on which they were modified.

4.10.7 Hermeneutic Visualizations

The rich text obtained from interactions with the study participants, their contributions to the StrC, and the data obtained from GA tools was used to produce hermeneutic visualizations (Rockwell & Sinclair, 2016), and to identify visual patterns within the collected data. Observing repetitions, variations, proportions, time-tracking, and other interpretative aspects across participants' responses and comments brought possibilities to adjust the interface during the academic prototyping process, and to continue developing the tools for future user studies and final deployment of a comprehensive StrC ecosystem for public use.

The hermeneutic visual representations used for analysis (described in Chapter 3.5.2) were quantifying word clouds (e.g., to visualize a group of authors by epistemologies in the literature review), bubble-packs (e.g., to show the overall distribution of visits to the StrC features), bubble-lines (e.g., to quantify the level of agreements-disagreements with several of the survey questions, and to subtract and quantify repetitions of keywords from the written responses), and variations of these combined with traditional chart visualizations such as comparative bars and distribution pies (e.g., to visualize demographic data). The data that feed these visualizations was obtained through GA tools, and manipulated with other publicly available visualization tools (i.e., Tableau Public,[74] Voyant,[75] and 7Vortex[76]). The process to create hermeneutic visualizations can be summarized as follows:

1. Data was collected from results from the study, from GA and Google Forms, and stored in spreadsheets.
2. Data from spreadsheets was copied, imported into visualization tools (e.g., Voyant) and manipulated using different tools (e.g., bubblelines).
3. The visualized data was exported as a graphic file (PNG and JPG) to Adobe Illustrator where the final versions were edited, refined, and ready to be placed in documents as print resolution images.

[74] https://public.tableau.com
[75] http://voyant-tools.org
[76] www.7Vortex.com

These visualization tools helped to reveal expected and unexpected tendencies from the study, coincidental and conflicting points. They also helped to identify aspects for further exploration (as developed in Chapter 5).

4.11 Benefits, Opportunities, and Limitations Observed

The StrC study presented benefits and opportunities. Findings from the study (fully developed in Chapter 5) demonstrate that the StrC is overall a concept with high potential. Based on the participants' responses, from the perspective of scientists and design practitioners alike, the StrC is worthy of development. In addition to this positive outlook from the research, a number of participants who contacted the researcher during the study manifested their interest in contributing and getting involved with the StrC beyond this dissertation project. Before and during the study, the StrC also captured the attention of potential partners and supporters for future stages in the development of the interface, although no details can be shared in this dissertation due to reasons of confidentiality. Overall, the project and the study served to initiate and consolidate a network of people interested in the future of the StrC as a research tool.

The StrC experience also offers the opportunity to branch out in three further areas of exploration:

1. As a case of biocentered design dissemination, with philosophical and epistemological implications.
2. As a case of rich-prospect browsing and academic prototyping applied as a binomial method of research.
3. As an incubator of new cases of biology-to-design structural colour implementation.

Future research work on the StrC (research, development, and publishing) may be focused on these areas.

The StrC study also presented limitations as a result of three factors that affected the outcomes: technical limitations, content limitations, and logistics limitations. These are summarized in the following subsections.

4.11.1 Technical Limitations That Affected the Quality of the Prototype Version of the StrC Interface

Access to external repositories was restricted during the study to a few sources and a limited number of entries (data on species). It was initially suggested that the StrC could be used with full potential if the database could be populated by accessing the full list of repositories suggested (listed in Section 4.2), but this goal was not feasible by the time the study began. Future stages of the StrC development will demand full access to these repositories.

Restricted functions in the StrC interface (i.e., the widgets “homology,” “phylogeny,” “research map,” and “evolutionary disruptions”) were only simulated to demonstrate the function, but were not yet interactive, due mainly to time and budget constraints. Further development of these features would be more beneficial at this stage of the study than at a later stage. The academic prototyping characteristic allows these kind of advantages.

Some compatibility issues across platforms used by the participants (different operating systems and browsers) created some additional delays (e.g., participants in China were limited because they could not access Google tools). The effect of these issues was marginal in relationship to the purpose of the study.

The StrC interface and database maintenance (back end) and technical support to the researcher during studies worked very well; however, some troubleshooting needed attention and caused initial delays. Also, hosting the StrC on a U of A server caused problems before the study, but these problems were solved by moving the database and the site to a paid server, and creating a new domain (strc.online) in which the final version of the StrC was completed and deployed.

4.11.2 Content Limitations That Affected the Depth of the Study

Initially the number of cases in the database was restricted due to limited access to repositories. About 240 species were manually entered into the initial dataset, which limited the experience with the StrC until external repositories could be accessed to collect species estimated in thousands (planned for future stages in the StrC development beyond this doctoral study).

Because structural colour is such a dynamic subject, with papers being published constantly, late scientific advances in the field were not fully represented in the StrC design features by the time the study began. The content was specifically focused on the essential classification of structures, variations, and combinations. These points remain constant across old and new publications. The accuracy of scientific contributions collected during the study can only be assessed by a peer-reviewing process after the study.

4.11.3 Logistic Limitations That Affected Participation in the Study

The relatively small size of the sample was appropriate for qualitative analysis (fundamentally important to this study). However, it may seem limited for quantitative results. The ongoing development of the StrC implies a growing community of users, which may provide opportunities to collect more relevant quantitative data.

Other logistic limitations were related to enrollment for the study. Contacting and inviting targeted participants (scientists and designers) by email required extra time, insistence, a follow-up mechanism, and contingency measures (Fig. 4.14). Eventual restrictions and email errors also affected the process of personal contact. These complications might demand closer attention when evaluating advantages and limitations of self-administered questionnaires versus interviews described by Bernard (1995). While these issues were addressed in a timely manner with minor adjustments to the time frame projected in the schedule, it was necessary to favour personal contact with potential participants and access to networks over sending general invitations (i.e., email lists and advertising posters). The availability of participants during specific periods of time (exam periods, holidays, sabbaticals, etc.) was also a factor that created some delays and/or lack of responses. Extending the waiting period required some minor adjustments to the schedule.

Another factor that prevented a few participants from either accessing the study page or the survey had to do with limitations to accessing Google Forms in countries in the Asia-Pacific (such as China and Singapore). However, participants in these countries could navigate the StrC interface and their interactions were measured by GA.

One of the contingency measures planned to prevent participants from omitting the survey (Chapter 4.7.4, p. 126) gave relatively good results but not complete certainty about collecting such responses on time (within the 8-week study period). This was noticed halfway through the study (week 4). As an extra measure, a prompt message was programmed to pop up after 4 minutes navigating the StrC interface (the average time-per-session tracked by GA during week 4 was 5 minutes and 43 seconds). The message asked participants if they were ready to provide feedback (while they were accessing the StrC) or if they needed more time before accessing the survey (Fig. 4.15). This measure worked as an automatic reminder, replacing a less-efficient manual follow-up process originally planned (by email). This solution minimized the risks of participants mistakenly leaving the study without filling out the survey; the ratio of responses accessing only the study versus accessing also the survey increased after week 4. By week 8 the expected quota of participants filling out the survey was reached, and the average duration per session increased to seven minutes.

In person or remote access to interview by selected participants who were living abroad required flexible dates and times due to different time zones. Due to budget constraints, travel arrangements to meet participants abroad was not an option. Time zone constraints were also an issue when it came to coordinating the availability of the interviewees and the participants. For these reasons, all the additional interviews were done by email. The quality of responses did not appear to be diminished.

The final factor that affected logistics and scheduling of the study was the process for getting ethics approval. This process took several weeks and required preparation and anticipation; time management and planning were crucial to get this procedure done on time. However, the amendments required to conduct the additional interviews by email, specifying the details and modifying the original ethics documentation, caused some delays at the end of the study, and slightly affected the pace of the data collection and data analysis.

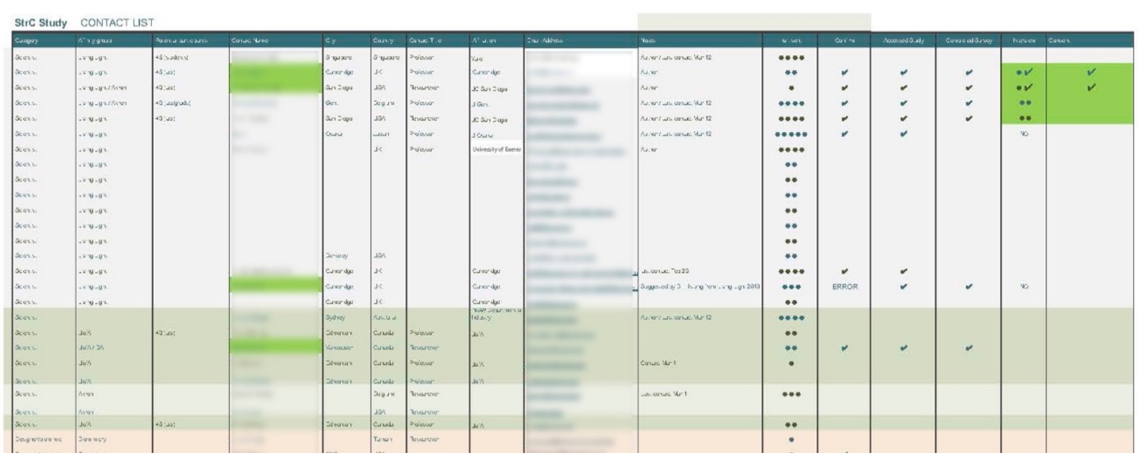


Figure 4.14. Screenshot of the follow-up spreadsheet for tracking contacted participants, number of attempts, errors, and contingency measures applied.

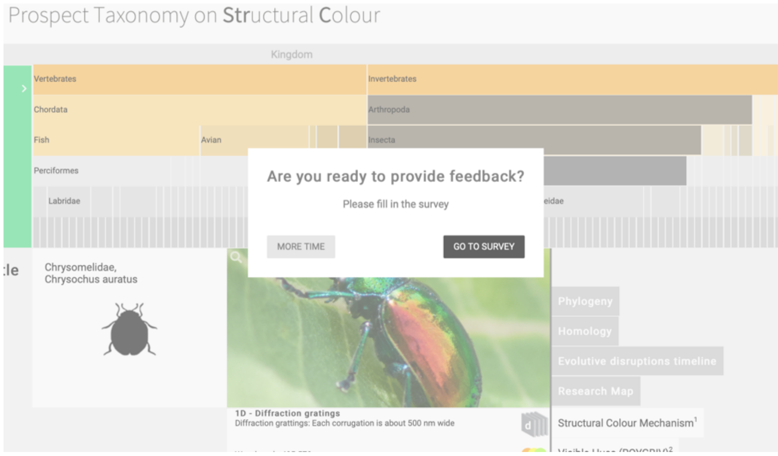


Figure 4.15. Window message after 4 minutes from opening the StrC website. It provided two options: the user could either request more time or access the survey.

Participants' responses to the online survey revealed a variety of relevant points and suggestions. The survey questionnaires about the StrC functionality and potential produced expected and unexpected effects on participants. Both the poor and the rich experiences exploring the interface ecosystem led to interesting new questions and important advice for further development.

Comments on issues regarding the user experience (UX) were taken into consideration for further studies on final versions of the StrC for public access. However, the goal of this study was not to obtain UX results; the primary intention of sharing the StrC with scientists and designers was to identify potentialities, common interests, and a common ground that would close disciplinary gaps in communication between such realms. Results from this study may benefit and accelerate the development and implementation of biomimetic design research and projects on structural colour, as is stated in the original research question.

4.12 Conclusions

This chapter described design preparation, logistics, and the implementation of the StrC, as an academic prototyping rich-prospect browsing interface intended to be tested as a tool to provide clues that address the initial research questions.

Reviewing taxonomy, phylogeny, and tree thinking concepts helped to encompass the scientific language in which information on structural colour is embedded. The chapter suggested precedent-setting cases of taxonomic databases and repositories that may influence the StrC's future conceptual or functional development. Initial scientific questions were anticipated as a consequence of the academic prototyping process, and the initial assumption of interdisciplinary gaps implicit in the research question was identified and linked to specific aspects of the data collected in the study.

The entire process of designing and developing the StrC prototype was described in detail, as were the planning, execution, data collection, and data analysis stages of the study. The chapter also examined the benefits, opportunities, and limitations observed during the design and development process. All this information serves to frame the analysis of the findings in Chapter 5 and the conclusions in Chapter 6.

CHAPTER 5: FINDINGS

This chapter presents results collected from the study (i.e., quantitative and qualitative data) and analyzes findings from the data. It offers different angles for interpreting such findings, with focuses on relevant points that address the main research question and on detecting issues that may facilitate implementing structural colour in biomimetic design practice. The chapter also summarizes the results of applying the methods and tools for research described in Chapters 3 and 4, the use of a rich-prospect browsing probe for academic prototyping, to collect and subsequently analyze the data. This analysis makes it possible to reflect on the level of success of the methods chosen and to identify milestones, turning points, and the pros and cons of implementing a research tool such as the StrC. This chapter also reflects on possible reasons for the negative as well as positive outcomes that resulted, and summarizes the elements for discussion and conclusions in Chapter 6.

On one hand, design researchers may see the findings on the use of a rich-prospect browser as a case of academic prototyping (Ruecker et al., 2014) useful to conduct other research projects. The StrC was also used as an informational probe (Crabtree et al., 2003; Hemmings et al., 2002) as a method for this study. Experimenting with alternative tools in a multiepistemological environment plays a central role in this experience. Researchers also may find, in the methods and outcomes of the StrC study, a precedent for research innovation (Oxman, 1996), with a gallery of data visualization tools combined in a way that opens new terrain for exploration and inspiration (Strickfaden et al., 2015). Scientists may find that these research tools provide opportunities to showcase the transcendent work they are doing on uncovering the secrets of structural coloration for inspiring design innovation.

On the other hand, through the outcomes of the StrC study findings, both scientists and designers may discover interesting points of coincidence between design and science thinking, and an opportunity to position themselves in closing the interdisciplinary gaps suggested by the initial research question of this dissertation. These disciplinary bridges may also interest researchers focused on addressing intradisciplinary design-to-design and science-to-science limitations that prevent innovation.

Finally, designers and scientists may see these findings as evidence of the potential and synergetic effect that a biocentered approach to innovation has when it comes to connecting different disciplinary realms.

5.1 Presentation of Findings

As stated in Chapter 4, this study aimed to provide quantitative-qualitative evidence of three overarching goals as subjects of analysis: (a) Measuring the level of interest of scientists to explore and contribute to the StrC; (b) measuring the level interest of professional practitioners and researchers interested in biomimetic design to explore the StrC and the subject of structural colour, following a biology-to-design biomimicry approach; and (c) detecting synergies between scientists and professional practitioners and researchers interested in structural colour and biomimetic design, by the evaluation of commonalities and convergences in the data collected.

The StrC study was open for data collection for a period of 8 weeks. In that period, there was a total of 61 visits, 31 consent forms submitted, and 19 completed surveys. The total number of visits included all users accessing the StrC interface online (see https://strc.online) during the period of the study, even those who did not fill out the consent form and thus were not considered as official participants of the study for qualitative research purposes. Casual visits to the StrC interface were included, however, as raw quantitative data collected by analytics tools.

One segment of the total visits was comprised of participants that accessed the study, read the information sheet, and filled out and submitted the consent form to participate through the StrC interface, but were not able to complete the survey (or opted not to) at the end of the experience. This might have been mainly due to availability during the time frame of the study; exploring the interface and responding to the survey required a minimum of 20-25 minutes, in addition to reading the information sheet, completing the consent form, and following the guiding points. Both scientists and designers+ (the two groups targeted), might have found it difficult to make the time to fully participate in the study in the given time frame, despite having high interest in the subject. Those who did not participate in filling out the survey were still able to add comments through the red layer feedback function, an equivalent to responding to open-ended questions. However this segment of participants seemed marginal to the qualitative purposes of the study.

The total number of 19 individuals who completed surveys represents participants who accessed the study, read the information sheet, filled out and submitted the consent form, and completed and submitted the survey. This last segment is the core of participants who offered more qualitative data to the study, and it was divided into two main groups: scientists (biophotonics, biology, and physics) and designers+ (design practitioners and other disciplines involved in biomimetics). From these participants, eight selected scientists were contacted by email to answer a few more questions in a semi-structured interview format, to obtain additional qualitative feedback, as described in Chapter 4.8.4 Four of these participants responded with additional thoughts to these questions. These questions were correlated to key discussions identified from responses in the survey. The discussions were intended to further explore underlying reasons that may prevent implementing structural colour, to collect insights and hypotheses, and reveal dominant trends across different scientific views.

The following summary of findings will be divided into two parts: quantitative findings from all visitors to the StrC, and a combination of quantitative and qualitative findings from study participants, primarily represented by the segment of scientists that responded to the semi-structured interview.

5.1.1 Quantitative Findings From All Visitors to the StrC Interface Online

React Analytics (RA) tools used in Google Analytics (GA) and set for this study provided quantitative data collected from visitors interacting with the StrC interface. GA "Audience Overview" figures revealed a total of 61 visitors (users) to the StrC site between January 15 and March 15, 2019.[77] Visitors accessed the site from 11 countries including Canada (Fig. 5.01) and 15 identified institutions[78] (from academia and from research and industry sectors, as mentioned by survey participants). The total number of sessions[79] was 150, with 1,694 page views[80] counted (Fig. 5.02), and an average duration of 7 minutes per session and 2.46 sessions per user. A quarter of the total visitors returned to the StrC more than once (25.3%) (Fig. 5.03). Returning users can be considered an indicator of engagement, since exploring the interface in depth with a certain level of reflection requires some time. Completing this process in several sessions is an indication of interest in exploring the interface. Within that quarter of returning users were the most engaged participants, with users spending up to 30 minutes on one visit. These results are

[77] GA tools made it possible to set a filter to prevent internal traffic from affecting the data collected. Traffic from IP addresses from the StrC researchers and developers was filtered out and not included in the data set.
[78] Information on participants' affiliations was obtained from the StrC survey (Google form) with the consent of participants, and not from GA.
[79] A session is the period of time a user was actively engaged with the StrC interface. All usage data (Screen Views, Events, Search, etc.) is associated with a session.
[80] Page views is the total number of pages viewed, including those visited recurrently.

only indicators of general interest and engagement, but do not replace qualitative indicators for the evaluation of the interface (an aspect covered by the contributions to the red layer, the survey, and email interviews conducted).

		61 % of Total: 100.00% (61)	61 % of Total: 100.00% (61)
1.	Canada	30	47.62%
2.	United States	15	23.81%
3.	United Kingdom	4	6.35%
4.	Japan	4	6.35%
5.	Belgium	2	3.17%
6.	India	2	3.17%
7.	Singapore	2	3.17%
8.	Switzerland	1	1.59%
9.	China	1	1.59%
10.	France	1	1.59%
11.	Vietnam	1	1.59%

Figure 5.01. Distribution of the StrC study visitors by country, obtained from GA.

Sessions
150
% of Total: 100.00% (150)

Pageviews
1,694
% of Total: 100.00% (1,694)

Count of Sessions	Sessions	Pageviews
1	59	794
2	19	366
3	12	76
4	6	60
5	6	64
6	4	14
7	3	25
8	3	6
9-14	11	62
15-25	11	100
26-50	16	127

Figure 5.02. Sessions' details obtained from GA. The count of sessions is ordered by the sessions associated with one visitor occurrence. For example, #1 in the "count of sessions" column is initial sessions, those that occurred with no prior session recorded (i.e., 61 first visits to the StrC homepage, which equals the total number of visitors); #2 in the "count of sessions" column is the sessions that occurred with one prior session recorded; #3 is the sessions that occurred with two prior sessions recorded, and so on.

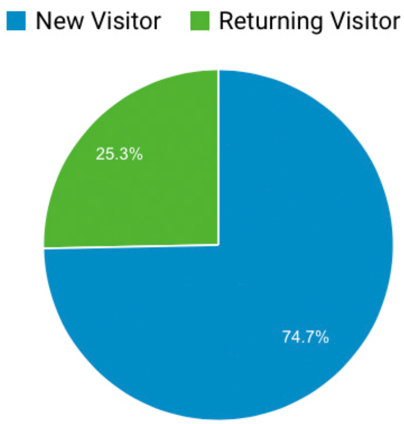


Figure 5.03. Returning visitors ratio obtain from GA.

It is worth mentioning that after the proposed targets in Chapter 4.7, 130 invitations were sent (to individuals and groups) to recruit participants for the study, and it took 76 follow-ups and reminder messages to secure 19 participants within an 8-week period; that is almost seven invitations (a ratio of 6.84) and four follow-ups on average to get one participant fully involved.

The level of success of recruitment methods can be also measured by GA data collected. Visitors that accessed the StrC interface were classified by GA according to four different types of traffic: direct,[81] organic search,[82] referral,[83] and social.[84] The distribution in these categories (Fig. 5.04) shows that most visitors (about 60%) accessed the StrC by direct invitation (through emails, social media, and shared link in person), while the remaining visitors (about 40%) accessed the StrC by indirect searches. It is important to note that, although part of the most common form of access (i.e., direct access), social media and referral remained marginal (2%) or

[81] Direct traffic is defined as URL's that visitors either type in directly or reach via provided link to access the site (Google.com). These visitors were mainly derived from email invitations.
[82] Organic Search traffic consisted of visitors that found the StrC website after using a search engine like Google, so they were not "referred" by any other website (Google.com). These visitors could derived from seeing the StrC poster, presentations or lectures about the project in conferences and other events.
[83] Referral traffic is any visits to the StrC that came from sources outside Google search engine (or Google forms), for instance hyperlinks to go to the StrC as a new website. These referred visitors can be consider part of the direct traffic, since the link to access the StrC was provided and shared from different sources.
[84] Social traffic were visitors accessing the StrC from social networks and social media platforms (i.e., Biomimicry and scientific networks in Facebook, Tweeter, Research Gate, etc.).

difficult to measure in comparison to either direct invitations or indirect searches. It is hard to verify whether part of the organic search was also derived in combination with social media. From these figures, it can be deduced that personalized invitations (by email and personal contact) were the most effective strategy for enrollment over other methods; however, presentations about the project in lectures, conference posters, etc. may have generated a high volume of organic indirect searches which were also effective for attracting visitors.

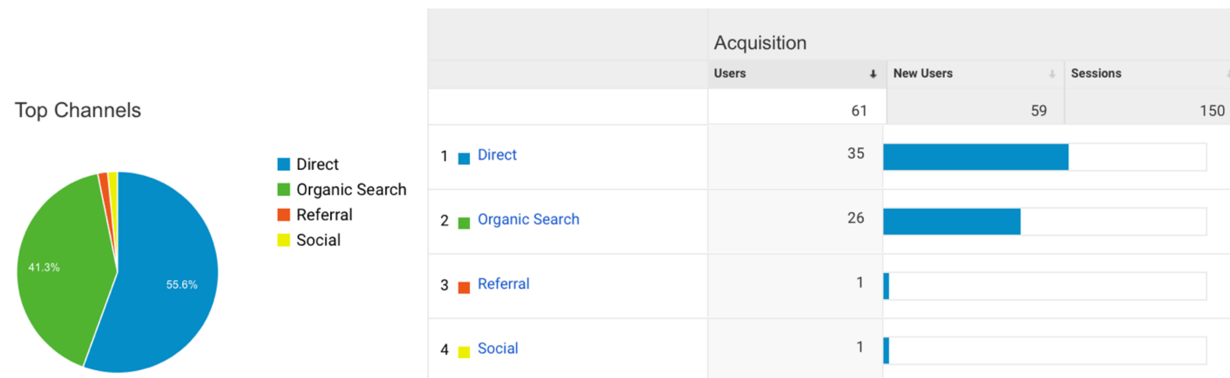


Figure 5.04. Distribution of recruitment channels obtained from GA.

"User Behaviour" figures from GA also revealed interesting quantitative data for the study; in particular the details collected as events[85] provide a variety of points for analysis. Events were grouped in five (non-hierarchical) categories (Fig. 5.05) labeled "taxonomy" (interactions with the StrC home page and species pages), "colour" (the resulting galleries of images from using the colour picker), "search" (from using the search engine), "widget" (from interacting with the widgets, *homology*, *phylogeny*, etc.), and "feedback" (from using the red layer to provide comments). The totals show that the main taxonomic features, home page, and species profile pages were, as expected, the most used (about 47% of events related). A less

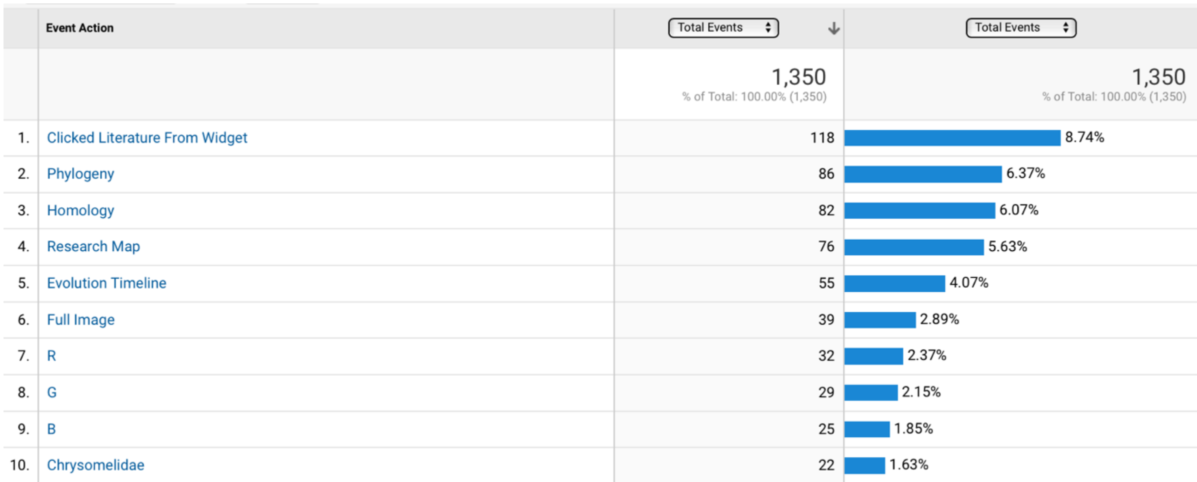
[85] Events are user interactions with content that can be tracked independently from a web page or a screen load (Google.com).

predictable outcome was the high level of interaction revealed in the widgets (about 37% of events related) compared to the colour picker activities (around 11%). This suggests that the widgets imply more complexity and demand more exploration (consequently more events), while the galleries of photographs resulting from interacting with the colour picker represent a somewhat more simple activity. This comparison does not necessarily correlate with the nature of the comments collected in the next section of this chapter (qualitative results from the survey), which suggests a high level of acceptance for the colour picker among designers, and a more critical position on the effectiveness of the widgets among scientists. Different interpretations are possible, but overall, reflecting on the fact that the most appealing and used feature of the StrC for both scientists and designers—the widgets—is also one of the most controversial points for future development, opens a dialogic space between scientists and designers, as is described in the next section.

	Event Category	Total Events	% Total Events
1.	Taxonomy	643	47.63%
2.	Widget	491	36.37%
3.	Colour	153	11.33%
4.	Search	52	3.85%
5.	Feedback	11	0.81%

Figure 5.05. Event categories measured in GA.

There were a total of 1,350 events (Fig. 5.06), repetitions included, and 260 event action types if repetitions are not counted, distributed in the five event categories. Individual events ranged from clicked literature from the word cloud, to accessing individual widgets, to picking individual colours with the colour picker, to finding individual species, details of that species, et cetera. The total number of events distributed in category clusters is represented in Figure 5.07.



	Event Action	Total Events	Total Events
		1,350 % of Total: 100.00% (1,350)	1,350 % of Total: 100.00% (1,350)
1.	Clicked Literature From Widget	118	8.74%
2.	Phylogeny	86	6.37%
3.	Homology	82	6.07%
4.	Research Map	76	5.63%
5.	Evolution Timeline	55	4.07%
6.	Full Image	39	2.89%
7.	R	32	2.37%
8.	G	29	2.15%
9.	B	25	1.85%
10.	Chrysomelidae	22	1.63%

Figure 5.06. Screenshot from GA showing the top 10 of 1,350 events (from a total of 260 event-action types).

From these figures it is possible to infer the effectiveness of the word cloud of authors (in GA this is labeled as the event "clicked literature from widget"). The word cloud of authors leads the ranking of individual events, followed by accessing the individual widgets (Phylogeny, Homology, Research Map, Evolution Timeline), the Full Images (from the species profiles), and the use of the colour picker (Red, Green, and Blue among the most chosen). The main taxonomy (the most visited category) is the most scattered group given the number and diversity of clickable elements available from the home page and species profiles (Fig. 5.07). The guiding points for participants (Appendix 7.1.5) suggested ways to navigate and find content in the interface. Not all participants followed these guiding points; however, a predictable result emerged: *arthropoda* and *chrysomelidae* were the most chosen categories, and *Chrysochus Auratus* the most chosen species. Not surprisingly, all three were suggested by the guiding points. Nevertheless, ranking the most clicked individual elements (events) of the interface reveals other interesting patterns of behaviour from participants that lead to qualitative interpretations. Also, the distribution and quantification of the totality of the events collected do offer good points for qualitative analysis. For instance, the colours red and green were chosen more times than blue, despite blue being a more predictable choice given that it is more abundant and iconic among structural colour cases (e.g., the morpho butterfly). It can be speculated that scientists in particular were more curious to explore which red and green structural examples were in the collection, since these structural hues are less common. In fact, one scientist detected that structural red assigned to an avian species may be not structural at all but pigmentary (the correction was sent through the red layer under "suggestions").

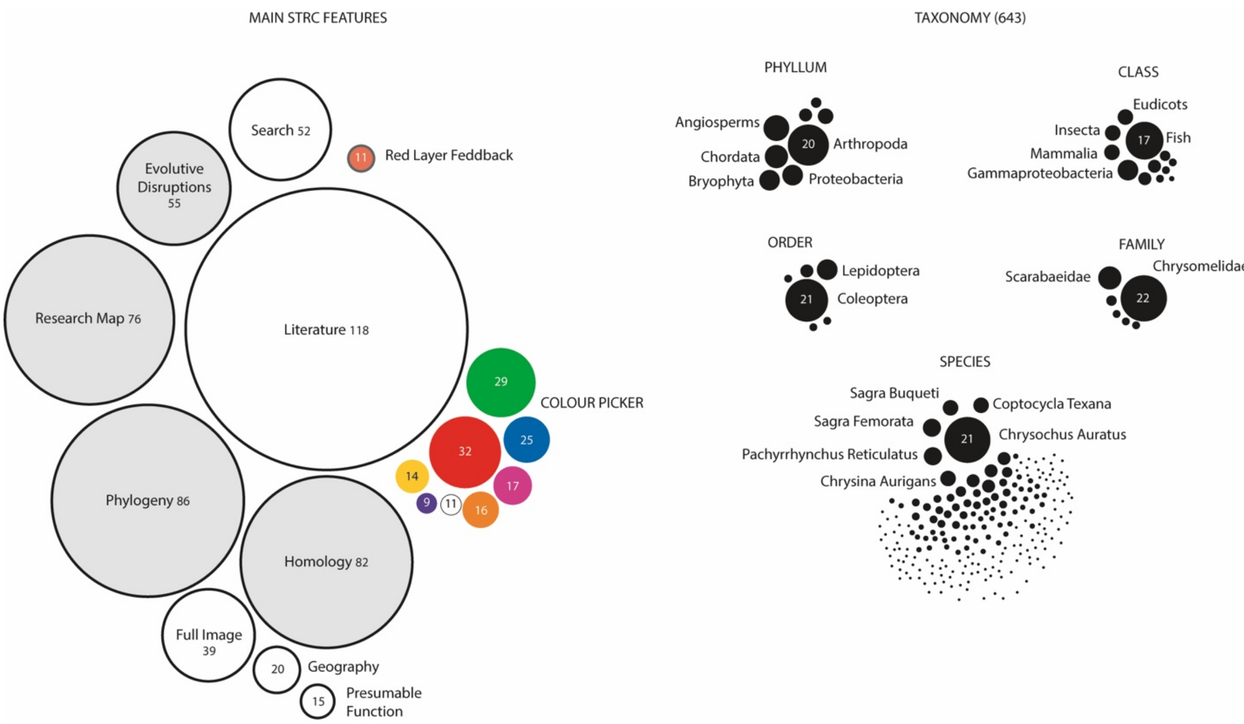


Figure 5.07. Bubble visualizations of the total number of events distributed in category clusters. Every bubble is an event, and sizes represent the number of hits an event received (number of hits is included in some bubbles).

Overall, the results collected by GA add up to a quite significant but somehow predictable outcome: the proportion of accountable events suggests the level of importance that participants confer to each StrC component. The taxonomy was by far the most attractive feature and the essence of the StrC, followed by the widgets (the "discovery tools"), the access to literature, and the colour picker (the "ludic" tool). The remaining less noticeable features may play a significant role in future development, but did not provide significant quantitative evidence for this study (e.g., the red layer). For this reason three more ways of data collection were planned; the survey, the contributions (even though there were only a few) from the red layer, and the interviews provided more input from a qualitative point of view, as described in the following pages.

5.1.2 Qualitative Findings From Participants of the Study

This segment consisted of the 19 participants who completed the questionnaire in the survey—14 of them also accepted being contacted for an interview (see details on p. 214). The segment also includes the participants who simply explored the StrC and eventually provided comments to the red layer feedback, but did not further contribute to the survey and interviews.

The qualitative responses were collected from two questionnaires included in the survey (Google Forms), the comments added to the red layer (API back end), and email interviews conducted. The following is the breakdown of responses grouped by survey section and question numbers, by red layer categories, and by the semi-structured email interviews at the end of the study.

5.1.2.1 Main Survey Questionnaires (Survey Section 2)

After filling in Section 1 of the survey (basic demographic information detailed in Chapter 4), participants were steered to Section 2 of the survey, the main two questionnaires: one for “scientists,” and the other for “designers+” (designers and other biomimetic practitioners). The following pages detail the responses collected from these two questionnaires. The collected information consists of quantitative data turned into hermeneutic representations, and qualitative data from responses to open-ended questions and additional comments. From this qualitative data, a selection of key comments was identified for analysis (Bernard, 1995). What follows is a summary of this collected information, organized by question order.[86]

5.1.2.1.1 StrC as a Suitable Concept for Developing a Comprehensive Research Tool [Questions 2.1.1 and 2.2.1]

While most participants agreed that the StrC is a suitable concept (82% of scientists and 87% of designers), a minority remained neutral (18% of scientist and 13% of designers). Little or no disagreement across scientists and designers also demonstrates high interest in the potential of the tool (Fig. 5.08).

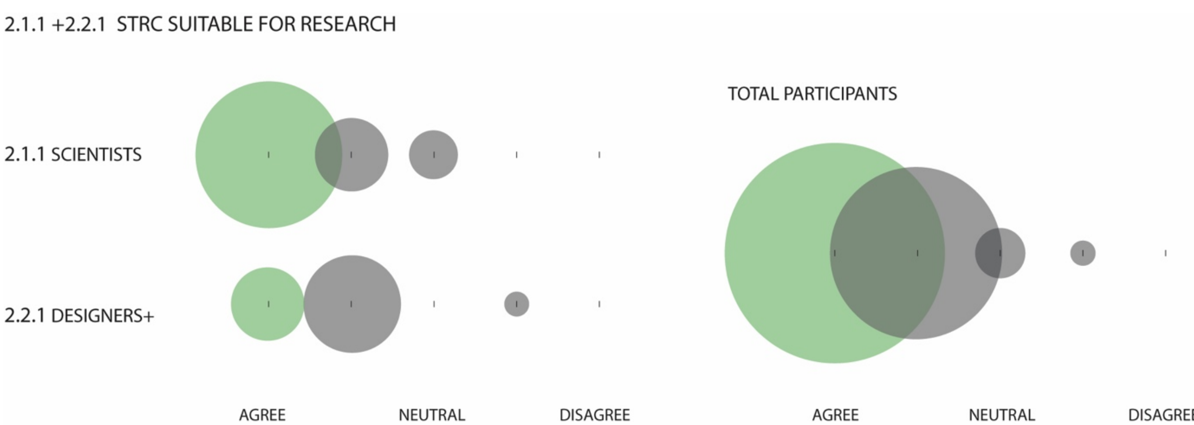


Figure 5.08. Level of acceptance across participants. The size of every bubble represents the number of participants with clear dominance of “agreement” over “disagreement.”

Participants’ comments were overall positive (e.g., “*This is a great idea, and I look forward to it being implemented”*—Scientist). The few participants that seemed reticent still displayed some optimism about the interface. One of them confirmed one aspect assumed in this research, that there is abundant scientific information available on structural colour, and that the StrC could be a tool for accessing that information: *“*[StrC] ... *needs to be linked to external existing databases to be useful in a very traversal way, **info are around, need to be collected somehow, but it is a great start**... ”* (Scientist). It is not surprising that the StrC may be seen as

[86] Some of the quotations are in bold. The author did that for reasons of emphasis.

neither entirely useful nor concrete enough (even naïve) in the eyes of scientists, who by nature are skeptical, or that it might not stand up to the scrutiny of user-experience (UX) designers (to mention one specific design area that concerns the development of tools like the StrC). This is not problematic for an academic prototyping case like the StrC. In fact, what the comment above recommends for the StrC is exactly what the StrC was planned for: to access external repositories for an automatized collection of already abundant data. Qualifying the StrC as "a great start" in this case is evidence of the interest in the potential of the tool.

Other comments from scientists pointed to specific details that reveal a higher level of interest. One scientist asked a question that is indeed a proposition to be considered for the future development of the StrC: *"Do you plan to include some synthetic examples that display mimicry of some of the biological structures?"* Synthetic examples of structural colour mimicry could be integrated in a new section of case studies on new materials and products. This was also anticipated in other comments: *"You might want to add a section on 'biomimetic materials,' where you can see what attempts have been made to replicate a certain structure. This could be a subcategory under species or even under colour"* (Scientist). These comments contain suggestions that should be seriously considered when planning for future StrC development. The original idea was to recommend AskNature.org to future users of the StrC who are looking for case studies of implementation; AskNature.org is a database intended for such a purpose. However, adding a section that provides such information to the StrC widgets or to the species profile, and a mechanism like the red layer, which allows scientists to contribute with study cases of implementation (on new technologies, materials, or products), would be a good feature for future improvement; this is mentioned later in this chapter under "Key suggestions to improve StrC features." It is also mentioned in Chapter 6.

Other comments about the StrC as a suitable concept pointed to specific problems of usability which are solvable design issues, such as trouble finding and understanding some functions; for example, *"If the search button was easy to spot, I struggle[d] to find the field where I was suppose[d] to type in."* It can also imply conceptual problems, like the Evolutive Disruptions widget, which is demonstrated later in this chapter: *"I couldn't understand how to get useful information for the Evolutive disruptions timeline section…"* (Scientist). Yet, such comments indicate a good level of interest in, expectation for, and engagement with StrC functions.

5.1.2.1.2 Correct Organization of the Taxonomic Content of the StrC (Levels, Categories, and Items) [Question 2.1.2]

Asking scientists—biologists in particular—if the taxonomic content of the StrC (levels, categories, and items) was correctly organized is a key component to evaluate the genuineness and effectiveness of the StrC as a research tool with scientific rigour. Of the participants, 73% agreed that the StrC taxonomic information is correctly organized, 9% remained neutral, and 18% disagreed or slightly disagreed. Disagreement was mainly due to fixable problems and inconsistencies within the lower level categorization, as is indicated in some comments below.

Additional comments showed the very positive initial reactions from participants who had significant experience in biophotonics and extensive knowledge in biomimetics (e.g., *"A lot of detail, I am having fun exploring the information"*). The idea of "having fun" while exploring the StrC seems essential to engage scientists and designers under same interests, and may also help in bridging interdisciplinary communication gaps.

Some participants detected a few problems and inconsistencies within the categorization, terminology, and content of the taxonomy, which suggests that scientists do not find the StrC fully reliable. Some of these issues were able to be fixed during the study (an academic prototyping characteristic explained in Chapter 3). Among the fixable issues were a mislabeled category (*"Arthropoda is listed under vertebrate"*) and a problem with the activation of some labels (*"Chrysomelidae text does not pop up when the box is highlighted"*). However, these kinds of suggestions were expected to populate the contributions through the red layer rather than the survey.

Some comments were also suggested through the red layer, and served to detect areas for future improvement (and/or discussion), as with the case of a consistent terminology: *"Seems to be a mix of taxonomic and commonly named groups? e.g., Amphibia and Fish (instead of Actinopterygii)."* Issues like this were also fixed during the study in an academic prototyping fashion.

The limitations of a work-in-progress academic prototyping case may be familiar to designers, but not to the scientists, who by nature are accustomed to a high level of rigour. Some comments like the following remarked on these limitations: *"Not able to verify in any detail. I hope it would be set up to 'talk' to other taxonomy databases, like the tree of life project, and be self-correcting."* This comment anticipates what the StrC should do in the future: "talking" to other data bases and eventually self-correcting or at least self-detecting which conflicts need to be corrected. While connecting to other databases (repositories listed in Chapter 4.2) is part of the long-term plan for the StrC, "talking" to them is a good suggestion for future development.

Scientists such as physicists or chemists (i.e., from disciplines other than biology) may find it difficult to respond to a biologically oriented question in the same way a non-scientist participant would; for example, one of the scientists (a chemist) was stumped by question 2.1.2: *"Not able to comment, you need a biologist."* This example can serve as an indicator of the epistemological divisions that exist even within similar epistemological realms in science.

5.1.2.1.3 Level of Interest in Contributing With Scientific Data to the StrC Database [Question 2.1.3]

Scientists were asked, *Would you be interested in contributing with scientific data to the StrC database?* More than half (64%) responded in the affirmative, 18% responded "maybe," and 18% responded "no" (Fig. 5.09). Negative responses could be attributed to either lack of interest, lack of time to contribute, or limitations of information or knowledge. Neutral responses could be seen either as hesitant or conditional, but not negative. "Maybe" can be understood as "I may have the knowledge, I may be able to contribute in the future, but I'm not sure if I would do so." The neutral and positive responses represent 82% of the participants who were willing to contribute.

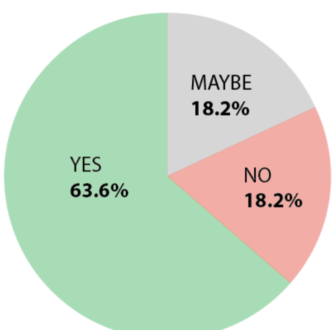


Figure 5.09. Participants willing to contribute to the StrC. The majority were willing to contribute, while a few remained reluctant or not interested.

There was a subquestion following the main question: *What would you contribute with?* This question was only addressed by participants responding "yes" to the first part, and their comments are summarized in the following list of possible contributions:

- *Species*
- *New publications (self and others)*
- *Existing primary literature*

- *Updates*
- *Amendments*
- *Data/photos for species (in general and species that scientists primarily work with)*
- *Structural imaging, Scanning Electron Microscopy (SEM), Transmission Electron Microscopy (TEM), and spectra*
- *Instances of arthropod data*
- *Mechanisms (more information on)*

The suggestions above are examples of very important content that could be contributed by scientists engaging with to the StrC, reinforcing the interface's role as a tool for both facilitation and collaboration.

Comments also reveal some risks of how contributing to the StrC may be perceived as a time-consuming endeavour: *"*[I may contribute with] *results of my research, and knowledge I have. However,* ***I wouldn't want to dedicate too much time to it. Filling all these fields of species may be very time-consuming****."* A more agile mechanism for contributions, designed to simplify this process, must be considered for future StrC versions.

5.1.2.1.4 Accuracy of the Mechanism, Structure, and Characteristics of Structural Colour in the Species Profile Pages [Question 2.1.4]

Scientists were invited to respond to the statement, *The mechanism, structure, and characteristics of structural colour in the species profile pages are well-described, illustrated, and accurate.* The intention was to trigger critical thinking that would lead to opportunities to find divergences and consensus on basic characteristics and definitions of structural colour. Scientists may not be engaged in an ongoing debate about mechanisms, structures and characteristics of structural colour, but neither have they reached a definite consensus on such definitions. Thus, the implicit suggestion is that the StrC is a space for multidisciplinary exchange and dialogue. "Well described, illustrated, and accurate" data, as the statement proposed, could in fact be a contradiction in the context of a work-in-progress academic prototyping process. The even distribution of results supports this point; 36% of the responses agreed with the statement, 36% disagreed, and 28% were neutral. There were no responses for strong disagreement. This may imply that some participants concluded that while the current prototype is limited, it is possible to make the StrC more scientifically rigorous and therefore more accurate.

This statement was (intentionally) provocative for participants who were experts in the subject of biophotonics. Today, it is hard for non-scientific audiences to reach consistent definitions on structural colour and such definitions may not be completely clear within the scientific community itself, especially when different disciplinary realms (i.e., biology and physics) are involved. The following two comments are a good example of this:

- *For many materials, mechanisms that cause structural coloration* ***are still of scientific debate****. It should be mentioned.* [Bold type used by author].
- *It is always difficult to ascribe one particular mechanism to a colour (researchers may disagree, or use different terms for the same mechanism), so this may need to be noted in some cases. It would be nice to see direct references to the primary literature from which this information was obtained (this holds true throughout the site).*

Key participants (those with a high level of knowledge on the subject) voiced contrasting opinions about the StrC characterization of structure and mechanisms of structural colour. This disagreement could be seen as evidence of an ongoing scientific debate about essential aspects of understanding structural colour. However, some other members of the scientific community believe that there is no debate, just semantic communication challenges on the way to arriving at common ground, as will be observed in the context of interview question 1 (p. 215). Structural colour mechanisms may be well understood but hard to define consistently.

Participants who agreed with the StrC characterization of structure and mechanisms of structural colour pointed out the merits of the interface: *"Very good level of detail in a very visual appealing format."* They also suggested opportunities for improvement: *"There are* *several aspect[s] and structures [that] can be hierarchical but [this] is a very good start and for some organisms it works really well."*

Other comments offered particularly interesting sugestions to enrich the StrC; for example, *"CIE['[]s values could be provided here[,] too."* For designers more familiar with colour industry languages (such as RGB, CMYK), CIE[87] colour mapping could be a useful addition to the StrC. Such suggestions to improve the tool also suggested a significant level of engagement and positive critical thinking toward the StrC concept; the following comments comprise a prescriptive list of improvements (some of which are included as recommendations in Chapter 6). All of these improvements are feasible design and development adjustments and additions:

- *Perhaps this is partly just an issue because this is a beta version with only a little data. It was not immediately clear that the lower-most panel is the symbol key for the center panel[;]* ***I'm not sure how beneficial it is to have symbols for everything.*** *Also[,] some of the icon/label/things in the magnified view didn't have a legend anywhere. It should be labeled what the inset alternate colour mode image is in magnified view. Rather than having an icon symbol for everything,* ***why not just embed an accurate and precise image, give the actual wavelength up front instead of a coloured circle,*** *etc[.]?*
- *Don't forget about structural black.*
- ***All SEM images desperately need scale bars.***
- *Would be much more meaningful to have reflectance spectra than a categorical colour assignment: of course,* ***if you include spectra you also need very thorough metadata about the spectra.*** *Lighting conditions, angle, objective lens, smoothing and other processing, reference spectra, etc. Should be able to access many different spectra from the same species, given that different conditions yield different information.*
- *… some phenomena, such as* ***light polarisation effects, seem neglected.*** *However, some species are sensible to light polarisation.* [Bold type used by author].

The above comments are excellent input to improve the design aspects of future versions of the StrC (especially the points in ***bold***). These comments can also be used to enrich the content on

[87] CIE is a colour space model to measure colour values, also called "colour gamut." This model was created by the International Commission on Illumination (CIE) in 1931, and serves as a standard for screen and printing industries when reproducing colour.

the physics of structural colour. The advantage of an academic prototyping probe format is that participants can provide relevant input based on what they can see and also on what they can imagine will work in the context of what they can see. One can speculate that asking scientists "what would you include in an application on structural colour" without accessing the StrC academic prototyping interface might not trigger such insightful comments.

5.1.2.1.5 Potential of the Widgets to Initiate/Expand Scientific Discussions Among Peer Scientists [Question 2.15]

Scientists were also asked to give their opinions on the widgets, the experimental components of the StrC environment. They had to respond by agreeing or disagreeing with the statement, *Widgets are useful to initiate/expand scientific discussions among peer scientists*. This statement was open to discussion and did not demand a deep analysis from participants, but rather was designed to make it possible to see the potential of the ideas. Nevertheless, it was still provocative given the level to which the widgets had been developed at the time of the study (they were only mockups, limited simulations; they were not working with real data from the database). Of 11 scientist participants, five (45%) agreed, four (36%) were neutral, and two (18%) disagreed (Fig. 5.10). Overall, scientists, even those who remained cautious, supported the potential of the widgets.

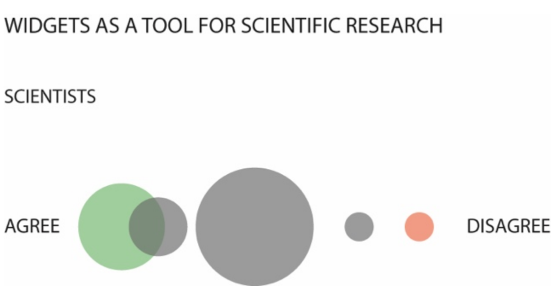


Figure 5.10. Widgets as a tool for scientific research. This visualization shows that most scientists either found the widgets useful or remained cautious about the widgets. The size of the bubbles represents the number of participants choosing from "agreement" to "disagreement" to the proposed statement.

The limitations of the mockup versions seemed to bias a few participants' responses to some extent. One of the participants expressed frustration with the feature: *"It would be very useful if the widgets works, it does not seem to work for me, or [it is] not intuitive to use. Therefore I cannot figure out how to use the widgets, and they have no value to me as is."* It can be deduced that the widgets looked perhaps too realistic to be only mockup versions, and thus it was hard for participants to recall that they were different from the rest of the features (as they didn't use real data), and had to be evaluated by their potential rather than by their current efficiency:

> *These [widgets] were somewhat unclear and non-intuitive to me. [I[[d]id not understand what evolutionary disruptions meant, or* ***from where the data were obtained.*** *The phylogeny was also not clear. [I] [c]ould not tell what it was supposed to show, or what species it included. [It] [c]ould be useful for discussion, but needs to be greatly clarified first.* [Bold type used by author].

Other scientist participants evidently understood that the widgets were just mockups not interacting with real data, and took them as an invitation to evaluate the potential developments linked to the second part of the question: *What discussion topics do you think could be generated from using the widgets?* The responses below illustrate this idea, and capture the spirit of the mockup versions in an academic prototyping context:

- *I really like the "Phylogeny" idea. I'd need to see a more complete version, but the basic concept looks really very helpful.*
- *[Widgets are useful to discuss] evolutionary convergence of structures… trends, similarities and their links to function.*
- *[Would widgets be useful to discuss] [the r]elationship to vision? Who sees the colour? Indicate whether colour is polarized?*

While the "homology" widget was very welcomed by participants as a feature with potential for research (see responses to questions 2.1.10, 2.1.12(d), and 2.2.10), the name of the tool is problematic. Generally speaking, homology means a classification of similarity often attributed to a commonality, which in a way is what the widget is trying to offer to the user by exploring and grouping commonalities in the collection. In biology, however, the term homology denotes a more specific meaning, one that implies the existence of shared ancestry between two species or genes, from different taxa. This problem of terminology was already anticipated by Dr. Tomislav Terzin (scientific advisor to this project) at early stages of the development of the widgets (former DTSC interface), but it was concluded that it would be interesting to hear from scientists how controversial this could be and what participants might suggest re-naming the widget. The following comment from a scientist corroborates the problem and also suggests "convergence" as an alternative concept, and goes even further by suggesting what this widget could look like:

> *…Not sure about "Homology"—since there are only 2 species included in the beta version, and* ***they are not homologous,*** *I can't tell how that widget is supposed to work. I'm concerned that it may be set up to* ***show me organisms with similar structures (good) but call them homologous (wrong).*** *"Homology" has a very specific evolutionary meaning; in a thorough database people could pretty much form ideas about homology just by looking at the phylogeny widget. If people just want to search for similar structures, that should be possible through the search tool, and should not be labeled "homology." "Homology" is not at all the same as "****convergence****."* ***What If, instead, you just made a tool sort of like the "colour picker" tool that lets me search up all structures with, for instance, a 3D crystal structure?*** [Bold type used by author]

Responses about the "evolutive disruptions timeline" widget brought mixed results from both designers and scientist participants' interpretations (see responses to questions 2.1.1, 2.1.12(d), and 2.2.10). Comments from scientists in particular were predominantly opposed to the idea. Designers, perhaps unaware of the implications of the concept of "disruptions" in evolutionary biology terms, were more open to exploring this feature, and even considered the concept to be a "game changer." (See response to question 2.2.10, evolutive disruptions timeline section.) The original intention of this widget was to open a "canvas" to be filled by scientific input, but criticism of this concept from scientists may discourage further development of the idea. As shown in the following comment, there are solid arguments that the idea is not viable:

> *… I do not like the "Evolutive Disruptions" widget at all.* ***That is not normal parlance for describing trait evolution****. I don't understand what the graph is trying to convey at all…What could this graph possibly represent that would be standard across organisms/structures? For example, maybe for a given taxon I could graph a change in the average density of scattering granules in a population over the past 100 years, but* ***that graph format would be irrelevant for most of the other organisms and structures in the database.*** *Please also note that you will not have any concrete information about the condition of structures over millions of years for almost any structure[;] moreover[,]* ***the current taxon designations aren't necessarily correct or meaningful over such long times,*** *and presenting it this way* ***is likely to lead people into misunderstandings"*** (scientist). [Bold type used by author].

Despite these negative aspects that make the "evolutive disruptions" idea too problematic (and are also in conflict with the designers' comments), criticism may also create new opportunities. For instance, what is being suggested by the "evolutive disruptions" widget could increase the relevance of the "phylogeny" widget: *"When people want to form hypotheses about how structures may have evolved over long time frames* [as suggested by the evolutive disruptions widget], ***they need to look at the phylogeny widget****"* (Scientist).

The concept and potential of the "research map" widget was somewhat appreciated. This widget was originally thought of as a static map for geolocation based on the origin of the institutions and authors, information that came from the literature available in the database. The widget was linked to particular species in the collection. However, adopting tools like 7Vortex[88] offers the opportunity to expand this idea into a more interesting and interactive metaphor, combining a map for geolocation with an interwoven ecosystem of networks and connections, such as labs and co-authoring groups. 7Vortex is still under development and not able to be embedded and fully functional as a StrC widget. This limitation might create some confusion (similar to other widgets' mock-up limitations):

> *I think the "Research Map" is a nice idea, although the current presentation is a little confusing. [The map in the background]…doesn't agree with the placement of people's*

[88] See an intitial map of the StrC literature here: https://www.7vortex.com/ecosystems/619fea2e-bbe2-44d2-9ecf-7a4cc722c177/view.

bubble names. I would simply want an easy way to find a researcher who has worked on a structure that interests me, or who works in a region I need access to, and ***maybe the literature cited section is already good enough for that.*** [Bold type used by author].

Overall, the concepts proposed by the four widgets were useful to initiate these discussions. Including the widgets in the academic prototyping experience served not only to provide useful input for future development of the StrC, but also led to suggestions of spaces to explore for the benefit of peer-to-peer scientific exchange and science-to-design exchange.

5.1.2.1.6 Other Data Visualization Tools to Be Included in the StrC Environment [Question 2.1.6]

Scientists were asked to respond the question, *What other data visualization tools would you like to see in the StrC environment?* It was a multiple choice question suggesting five standard types of charts used in science. It also gave the choice of "other" to point out other aspects or data that could be visualized in the StrC environment. The distribution of choices was ranked as 1) scatter plots, 2) distribution pie charts, 3) quantitative bar charts, and 4) comparative bubble charts (Fig. 5.11). A fifth choice, "impact polar charts," was not chosen.

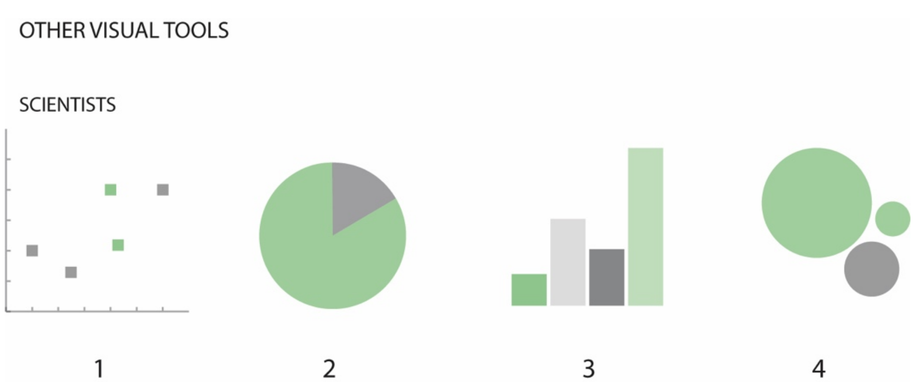


Figure 5.11. Other data visualizations tools suggested for the StrC environment: 1) scatter plots, 2) distribution pie charts, 3) quantitative bar charts, and 4) comparative bubble charts.

Comments collected under the "other" option characterized the quality of graphic representations that a scientist in the area of biophotonics might consider useful for standard research:

> *I would like to see much more detail for cataloging spectra, set up to allow me to access multiple different spectra for any one taxon (e.g., from multiple individuals or populations, from multiple angles, possibly in both laboratory and natural environment lighting conditions, etc[.].*

Other comments suggested that a scientific audience may be saturated with visual information in an environment like StrC, although according to scientists, the use of visual tools to better communicate science to designers may justify the inclusion: *"From a scientist's perspective, fewer visualization tools [may be needed], but I can understand how that's appealing to designers."* This indication is key to expanding the concept to and facilitating the experience for non-scientific audiences.

5.1.2.1.7 StrC Features Appealing to Designers [Questions 2.17 and 2.26]

Scientists and designers+ were asked, *What features do you consider appealing to designers looking for scientific information on structural colour?* This was a multiple choice question on the four main features of StrC, and an open-ended option for additional comments. The colour picker was the most chosen feature (73% of scientists, 75% of designers); the overall visual taxonomy followed in second place (54% of scientists, 50% of designers); the species' profile pages was in third place (54% of scientists, 38% of designers), and the widgets was the least-chosen option (27% of scientists, 12% of designers). The coincident order that resulted from both groups, and from a similar proportion of participants (11 scientists and nine designers+), indicates that the participants were in full agreement about the importance of StrC's main features (Fig. 5.12).

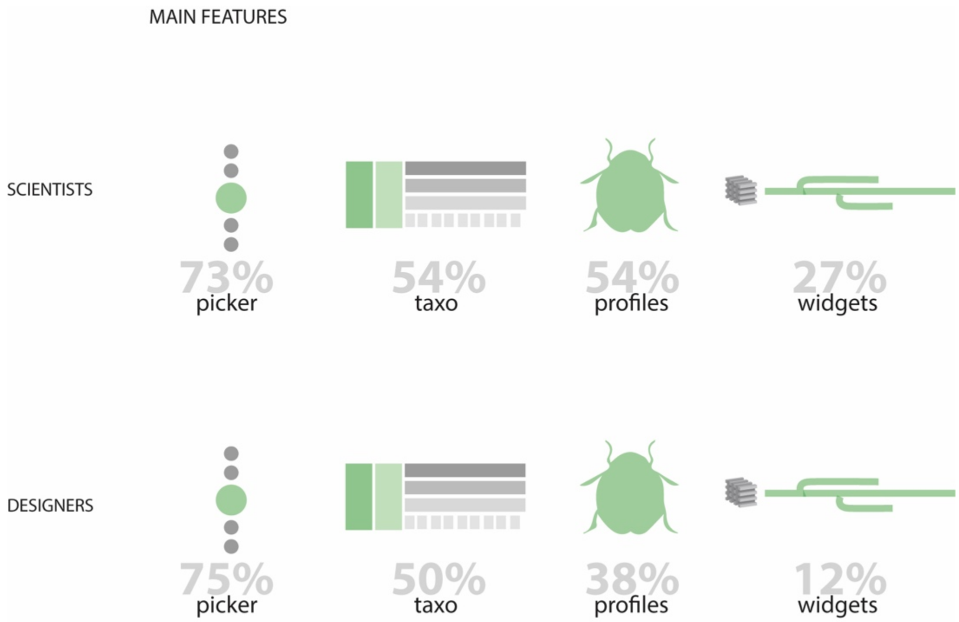


Figure 5.12. Preferences on main StrC features, ranked by participant group. Scientists and designers+ gave the same classification order from the most to the least appealing feature.

An interesting point from these results is the balance between the relevance and appeal of these features, implying functionality versus aesthetics. At the ends of the spectrum, widgets are the least appealing feature and the colour picker is the most appealing. Further comments, though, demonstrated a different perception when evaluating these same features as research tools: while the widgets were considered more useful, suitable, and possessing more potential, the colour picker was considered an interesting tool mostly for designers but not relevant for scientists. Thus, it can be deduced that appeal and associated concepts like aesthetics and eloquence are divergent from scientific relevance and associated concepts like rigour, accuracy, intuition, and truthfulness. In other words, and following this reasoning, appealing tools may not necessarily be conducive to practical outcomes.

Additional comments (from scientist participants only) were collected under the "other" option, and revealed critical as well as mixed opinions. Whereas the StrC seemed more "pleasing" than "functional" to some scientists (e.g.,*"The interface is visually pleasing, but the* *function of each area isn't very intuitive"*) for others, it seemed to be a wide-ranging useful prospect, not only aesthetically but also functionally:

> *What we actually need most, to trace photonic structure evolution better, is more attention to biological variation in the structures.* ***I really like how this site could help me look at variation in structure between species or genera, in the phylogeny widget. But we also need many more surveys of lower level variation, such as between populations and individuals.*** *I'd love to see this site set up to encourage that. Even just reporting the mean wavelength, the variance, the sample size, and what those samples were would be very helpful (as opposed to reporting just one wavelength value per taxon)* (scientist). [Bold type used by author]

This comment encourages the full development of StrC features as a tool for research. Some scientist participants took this project to the next level, making more useful suggestions to enrich the quality of StrC content:

> *There should be more attention to metadata about the specimen that people use to describe a structural colour. For example, exactly where was it collected and when? Is it an old museum specimen? Was it farmed? Did the researchers only look at one individual?* ***Frequently these details aren't readily available, and that is quite a challenge for talking about structure evolution and function*** (scientist). [Bold type used by author]

The comments above imply major challenges to a tool like the StrC, at least in its initial stages. Funnelling the metadata to the level of individual specimens can be a monumental task for any database, and participants admitted the scope of the challenge: *"I know that solving that* [collecting metadata on individual specimens] *is beyond the scope of this interface, but maybe the site's design could nudge non-biologist researchers to think about paying more attention to those details."* Yet, citizen science[89] databases such as iNaturalist.org cover a wide range of cases targeting that level of detail. iNaturalist and such databases (listed as repositories in

[89] Citizen science is a digital tool of scientific research conducted in part by amateur and in part by professional scientists (e.g., websites like iNaturalist or apps like Seek or NatureLynx). Any user of a citizen science tool is able to upload photos of specimens and share any information about the speciments. Later, this information can be curated and or completed by peer science reviewers.

Chapter 4.2) can be a strategic source of data for the future development of the StrC. What these scientists proposed is anticipatory.

Other suggestions appear to be more feasible from data and design perspectives. Again, iNaturalist and similar repositories could be good sources of information for geo-mapping these details at the level of individual specimens but also at taxonomical levels:

> *The geography* [in species profiles] *needs the ability to be much more detailed. So does the part about habitat* [“Ecosystem” section in the StrC]**. *I would like the map to show the exact range, and perhaps to highlight where the specific specimens whose photonic structures were characterized were from. I'd like to know things like elevation and more detail beyond just “forest” etc.*** (Scientist) [Bold type used by author]

A targeted improvement for the StrC should be to combine ecosystem mapping tools from iNaturalist, Ecoregions,[90] et cetera, similar to the ways in which AskNature.org or 7Vortex have contributed to this project. Linking geographic location and habitat data to studied photonic structures could be one of StrC’s most significant contributions (Fig. 5.13).

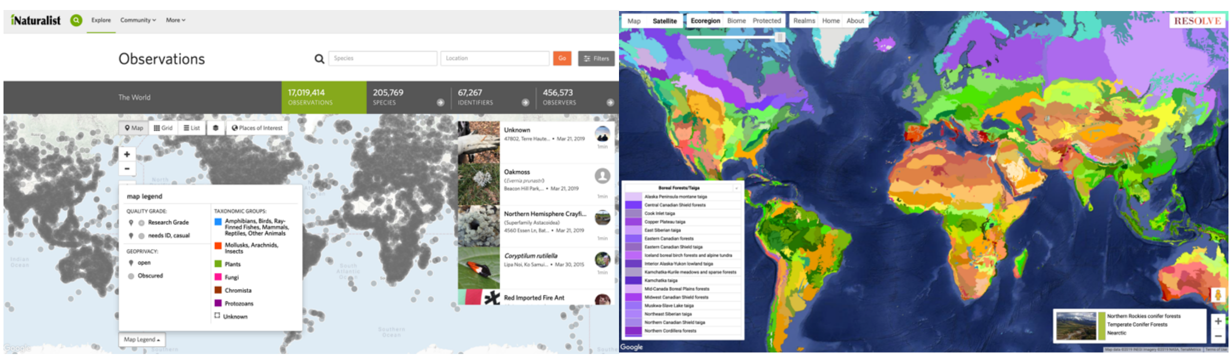


Figure 5.13. iNaturalist (left) and Ecoregions (right) use Google Maps services to geo-locate contributions, and give comprehensive details of ecosystems respectively. Tools like these two examples could be integrated into the StrC environment in the future for the “Geography,” “Ecosystems,” and other features to link geo-locations.

Other functions from the species profile also received useful criticism:

> *The function* [“Presumable Functions” in species profiles] *needs to be expressed much more tentatively—testing the ecological function of a structure is very involved and there aren't definitive answer[s] for very many structures.* ***I’d recommend labeling it as***

[90] Ecoregions is a world map of biological diversity distribution organized by colour-coding. See: https://ecoregions2017.appspot.com

> ***"possible functions" or "suggested functions" and then linking directly to the literature when you click on "expand."*** (Scientist) [Bold type used by author].

The term "presumable" can be acceptable as an assumption, and may suggest information "close to be true," which may not be the case in many believed functions associated to strucutral colouration. The suggested terms, "possible" or "suggested" may express better the idea of a speculative exercise implicit in this feature.

Widgets and the colour picker, opposites in this ranking of preferences on main StrC features, are central to scientists' scrutiny. Although the widgets were the less popular choice, "phylogeny" still seems to be an important design feature, as some comments suggested. Criticism of the colour picker can be used to improve the feature significantly, as this comment suggests: *"I might rather search by wavelength ranges than by arbitrary colour picker categories."* The picker idea could be expanded to offer other, more relevant information in addition to the simplified idea of colour hues:

> *People might like a way to search for structures that are dynamic, that are iridescent or not, that do or do not circularly polarize light, etc. Basically a way to search by optical functions that a designer may want to mimic.* (Scientist)

The comment above is key to repurposing the colour picker as a more rigorous and scientifically useful tool (this is later discussed in questions 2.1.7 and 2.2.6). A slider to navigate accurate wavelength ranges combined with the colour picker may be the solution. But it would also be an asset to augment the tool's capacity to search by optical functions (listed as a recommendation in Chapter 6).

Adding CIE values is another good suggestion, which was among the comments collected in response to this question, and was also mentioned in question 2.1.4. A colour gamut is a useful reference for colour industries, particularly for printing and paints. A colour gamut map (Fig. 5.14) including RGB, CMYK, and wavelength values equivalent to structural colour hues observed, could be included as a feature for species profiles or work within the widgets.

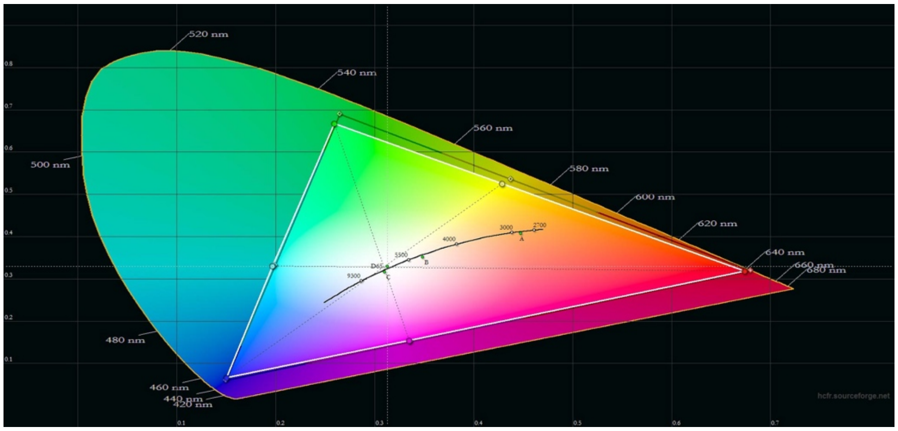


Figure 5.14. The CIE gamut diagram mapping the visible spectrum to human eyes (the whole coloured area) in comparison to colour reproduction technologies (depicted as the interior triangular areas). All the different technologies available, from printing to screens, cannot reproduce all the possible colours that humans (and other species) can see. Mapping structural colours in this diagram measured by their wavelenght values may require placing those colours outside the gamut of human vision (e.g., ultraviolet to infrared values). Image retrieved from https://www.flatpanelshd.com/pictures/panasonicdx900dci_large1.jpg.

5.1.2.1.8 Potential Biomimetic Design Areas to Apply Structural Colour [Questions 2.1.8 and 2.2.7]

Both scientists and designers+ were asked, *What areas to apply biomimetic design on structural colour do you see with potential?* This question was intended primarily to detect agreement in areas where designers and scientists could explore implementing structural colour and contribute to the field, and indirectly to assess the level of scientists' and designers+' knowledge about applying biomimicry. The multiple choice list included five options of different industries and technologies, the option "don't know," and an open-ended "other" option.

"Printing industry" was the most chosen option (54% of scientists, 63% of designers), followed by "paint industry" (73% of scientists, 50% of designers), "textile industry" (63% of scientists, 75% of designers), "electronic displays" (63% of scientists, 63% of designers), and "signal and communication technologies" (45% of scientists, 50% of designers). The "don't know" option received marginal responses (9% of scientists, 0% of designers) (Fig. 5.15). The number of responses under the "other" option was also marginal but relevant in content; the suggested areas with potential were "biosensing," "dynamic colour," "smart cities" (colour indicators), "marketing," "building materials," and "camouflage."

Figure 5.15. Ranking of structural colour applications suggested by participants.

5.1.2.1.9 StrC as a Communication Tool for Scientists and Designers Interested in Biomimicry Applications [Questions 2.19 and 2.2.8]

The statement *StrC can also be a communication tool for sharing, discussing[,] and get[ting] in contact with the scientific and design community interested in biomimicry applications* was presented to participants, who were asked to agree or disagree. This statement might sound ambiguous to some participants; however it revealed interesting signs on addressing the research question of this study—helping to bridge gaps between scientific knowledge and biomimetic design practices. Overall, both participant scientists and designers+ agreed that the

StrC can be a communication tool for sharing and networking (64% of scientists, 75% of designers+), while a smaller number remained neutral or more reluctant (36% of scientists, and 25% of designers+) (Fig. 5.16).

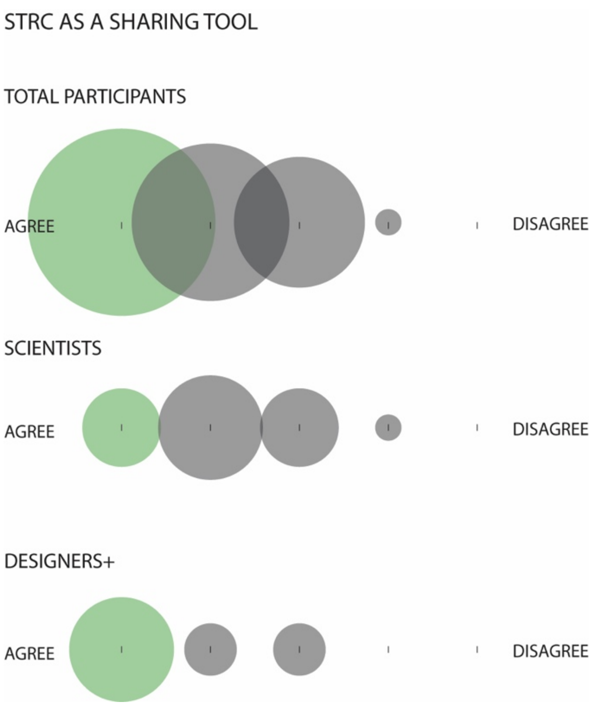


Figure 5.16. The StrC as a sharing tool. The bubbles show that most designers were more engaged than the scientists with the idea of partnership. The size of every bubble represents the number of participants choosing the options from "agreement" to "disagreement."

The second part of the question was: *Would you use StrC for sharing, discussing[,] and keeping contact with the scientific and design community interested in biomimicry applications?* It was intended to test the level of interest or possible engagement of participants using the StrC as a communication tool in the future. The scientists were noticeably more receptive to this, while the designers+ remained more reluctant. Four participants responded "yes" (64% of scientists and 0% of designers), 11 responded "maybe" (36% of scientists and 87% of designers), and four responded "no" (28% of scientists and 13% of designers). The additional comments help to understand these figures. Despite the wide-ranging aspect of the question, the potential of the StrC as a cross-collaboration tool is connoted in some of the comments. These comments synthetize the ethos and challenges of the StrC; for example, *“*[The StrC] *could become a powerful hub for colour researchers, but requires buy-in and openness”* (Scientist).

There is an assumption that designers are inclined to interdisciplinary practice, while scientists are more reluctant to embrace it. Initially, and intuitively, this assumption seemed reasonable when designing the StrC communication features. The expectation was that it would be more practical to help designers find scientists than the other way around. However, after analyzing the figures above, it appears that finding designers may be as important as finding scientists for this aspect of the StrC. The following comment confirms this: *“I can see how StrC could help me find researchers, but not really how it could help me find engineers/designers. Maybe it would just help them find me?”* (Scientist). This said, facilitating scientists to meet biomimetic designers would be an asset for the StrC. Right now this option is only available through the link to AskNature.org, which is possibly the best database in existence on biomimetic case studies organized by function. It would be challenging to include more case studies of implementation and materials and products under development derived from scientific literature (as suggested by participants in question 2.1.1). However, this is a challenge that the StrC should attempt.

This study did not merely check the validity of the StrC as a concept, it examined its efficacy to address the research question and its potential to act as a bridge connecting disciplinary realms. Nevertheless, the general tone of many responses was strong support for the StrC initiative, explicitly (e.g., *“Thank you for doing this!”*—Scientist), or implicitly (e.g., *“Of course, this [the success of StrC as a communication tool] depends on the size of the ‘StrC community’…”*—Scientist). Suggesting a “StrC community” (of scientists and designers+) is a sign of openness and support, relevant for addressing the research questions of this project. This support is also a good example of a subconscious clash of intentions among scientists, who seem cautious about opening their research to other disciplines (or at least to "talking" in different disciplinary languages), but, at the same time, need their work to reach other disciplinary realms (e.g., materials engineering, biomimetic design) and have a sense of urgency about this need. The StrC is positioned at the center of this tension, ideally as a facilitator and mediator.

Other participants suggested adding chat tools from social media to the StrC, such as *"Slack*[91] *portal or chat room"* (Scientist). This is a concrete sign that participants consider the StrC to be a sharing tool to connect peers and other disciplines' practitioners.

Comments among participants who remained neutral or more reluctant to the idea of the StrC as a communication or social media tool indicated that there is some ambiguity or lack of clarity in the way the initial question was posed; for example, *"Not sure what you mean by using it as a communication tool"* (Scientist). Comments also suggested that including applications from social media such as chats, forums, messaging, et cetera, might make it easier or more intuitive to understand the role that the StrC could play as a communication tool.

5.1.2.1.10 The Widgets as Tools to Discuss Existing and/or New Theories and Hypotheses [Question 2.1.10]

In this question, scientists were asked to rank how the widgets would serve best to speculate about existing and/or new theories and hypothesis. The intention of this question was to complement the findings from questions 2.1.7 and 2.1.5. It was expected that the responses justify the effort to further develop the widgets, as well as to detect which widgets had more potential. The ranking shows that homology was the most preferred widget (chosen by 45% of the scientist participants) for discussing theories and hypotheses, followed by phylogeny (second

[91] Slack is a collaboration digital tool that works as an app with cloud-sharing features.

choice, 37%), research map (third choice, 63%), and evolutionary disruptions (last choice, 82%; Fig. 5.17). These figures mainly support the idea that the evolutionary disruptions widget is conceptually problematic (as discussed in question 2.1.5), while the other three seem more practical or at least would be interesting if properly developed. That said, evolutionary disruptions was also chosen first by two scientists (18% of sample), which indicates that there is at least a conceptual if not a practical interest in the proposition. With a certain level of agreement on the content, parameters, and variables of the data, and an accordingly suitable redesign, the concept of disruptions could still be useful either as a widget for research or embedded in one of the other widgets (e.g., phylogeny).

A comment about question 2.1.5 (p. 180) suggested that "homology" might not be a proper name for that widget in biology terminology. Although some ongoing scientific debates reflected in such comments may offer important points, the intention of the StrC is not to confront different opinions or adopt all the suggestions offered, but rather to facilitate communication among interested parties with different opinions. Nevertheless, in further development of the StrC, the name "homology" for the widget may be reconsidered. Changes like this were not likely to be done during the time of the study; however, such a change is a feasible academic prototyping fix.

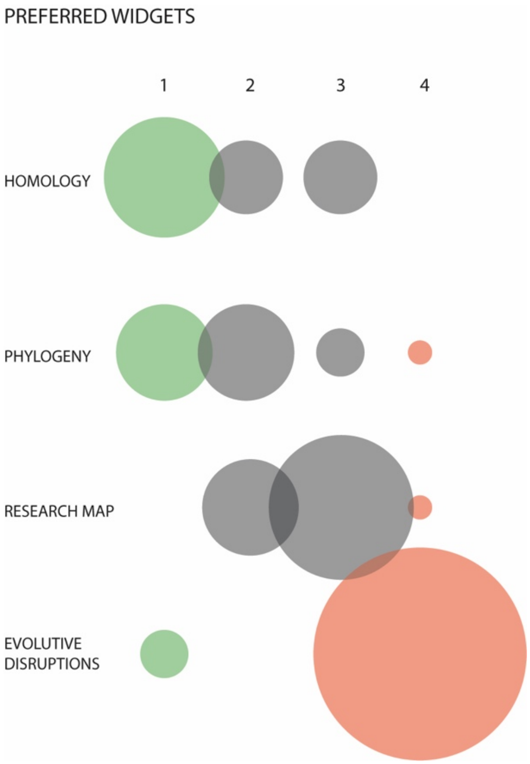


Figure 5.17. Preferred widgets. The size of the bubbles represents the number of participants ranking their preferences for first, second, third, and last option. Phylogeny and Homology were the most chosen as the first option, while Research Map was the most chosen as the third option, and Evolutive Disruptions was the most chosen as the last option.

5.1.2.1.11 Identifying Patterns, Convergences, and Evolutionary Similarities by Grouping Colour Hues [Question 2.1.11]

The colour picker and search functions make it possible to group taxa by their apparent colour hue. While this method does not intend to be accurate or scientifically rigorous, it may serve as an entry point to investigate scientific information. Scientists were presented with the following statement, *The collection of cases grouped by colour hue may showcase evidence on patterns, convergences, and evolutionary similarities*," and then asked, *What observations can you make about particular hues based on the number of cases? (e.g., the abundance of structural blue vs. structural red).* This is a teasing question for scientists, but nevertheless an invitation to test the role that the StrC may play as a tool for research. Comments collected covered a wide range of responses, from the straightforward, such as *"Green and blue are common"* or simply

"Agreement," to more elaborate and thoughtful, such as *"The more species using any given colour, the more habitats/environments exist where this colour provides some kind of evolutionary advantage."*

All of the comments were very constructive. Some focused on a critical and practical perspective, and provided good points to develop a more comprehensive StrC environment in the future; for example, *"I think that it is better to do this by structure than by colour[;] I am not sure you gather here much..."* (this suggestion was also made in response to questions 2.1.7 and 2.2.6).

Using formally designed tools like StrC features to group taxa may create spaces for scientific dialogue and debate, as suggested by the following comments:

- *Indeed, researchers can speculate on the number of cases. Of course, this will depend on the exhaustiveness of the db* [database].
- *I strongly agree,* [in that] *structural blues are much more frequently occurring than reds.*
- *I think it's an interesting question* ["*the abundance of structural blue vs. structural red"*] *…why we aren't aware of as many structural reds. I definitely wouldn't make any statements about the abundance from a beta version database. :) I also wonder if there's a researcher bias... like, people find more structural blues because when somebody sets out to study structural colour, they already know blue pigments are rare, and so they start off looking for blue. In any case,* ***it is fun to look at examples grouped by colour. [I] Still think looking by wavelength ranges might be more helpful.*** [Bold type used by author]

The conversation on abundance of structural blue versus scarcity of other structural hues continued in the interviews (see interview answers to question 4 on p. 219). Other comments speculated on the abundance of hues associated with function. One scientist suggested that the StrC could be used to discover relationships between biological functions and certain hues: *"Perhaps discover instances of aposematism associated with short wavelength hue,"* while other scientists suggested that using the StrC could help studying diversity of hues and iridescence associated to function: "[I observed…] *diversity of blues and 'position' on the organism for* *implementation of function," "All reds I saw were iridescent (one exception was pigment-based)."* This conversation on function associated with an abundance of structural colour hues continues in interview question 2 on page 216.

To summarize all the comments above, two scientists agreed that it may be more beneficial to customize and study a selection of cases from the collection by structure rather than by colour (as is also discussed in questions 2.1.7 and 2.2.6). Also, functions could be associated with grouped hues, such as instances of aposematism associated with short wavelength hues (blues to ultraviolet). The abundance of blue structural colour is directly proportional to the absence of blue pigment, and this proportionality could apply to any colour, for instance the scarcity of red structural colour and abundance of red pigment. This observation may bias the way we look at and the attention we pay to some colours. The presence of iridescence may be affected by these phenomena, too.

5.1.2.1.12 Additional Feedback About the Design and Content of StrC
[Questions 2.1.12 and 2.2.9]

Scientists and designers+ were asked to provide additional feedback on the StrC design and content, responding to the following statement: *Please provide additional feedback, comments, and suggestions about the design and content of the following StrC features,* being the options: (a) *the overall StrC interface environment*, (b) *the main taxonomy*, (c) *the red layer for contributions*, (d) *the widgets*, and (e) *the colour picker*.

(a) The Overall StrC Interface Environment

There was a very positive general response to the interface environment from across scientists and designers+, and constructive criticism with suggestions that may help to improve future versions of the StrC. The following list of comments summarizes this positive feedback:

- [The overall interface] *looks very visually appealing, still some kinks to work out* (Scientist).
- *Nice to look at, and fairly intuitive* (Scientist).

- *Seems quite appealing. Maybe the grey sections for the families and species may be a bit small but I suppose this will be unavoidable due to the number of species* (Scientist).
- *Love the style and interactive layout[.] I spent a long time looking [at] and exploring the site. And plan to look through it multiple times* (Scientist).
- *The top portion is beautifully laid out with a great intuitive form of navigation…* (Designer).
- *Nice interface–intuitive* (Designer).
- *The overall interface environment was quite intuitive. I found myself using the colour picker tool constantly. I believe that is a very strong asset for StrC. To be able to see the use of one colour across many different species is quite fascinating* (Designer).
- *Intriguing structure and flow of information, first left to right, then top down...multi layered arrangement and easy to navigate, intuitive* (Designer).
- *This looks great! Would sort species by [L]atin name if it makes sense to do so* (Designer).
- *I love the fact that the tool goes beyond providing information about colour. It also discusses the geography and ecosystems the species belongs [sic] to. Knowing the species' habitat and the environment influencing the species' colour is quite helpful* (Designer).

On the one hand, most scientists and designers+ agreed that the interface was, overall, effective even though it is a work in progress (as implied by the fact that it is an academic prototype); this suggests an important step in bridging disciplinary realms, the "design language" seems useful to the "scientific speakers" and the scientific content seems attractive and even exciting to the designers. On the other hand, some of the same designers who agreed with that were also more critical about the design usability aspects:

> *…the bottom area, the profile page, could be improved a bit. The data seems to be disconnected and not necessarily laid out to tell a story like the top portion. The proximity of information to each other, the information itself (details) could be increased. Maybe there is also a way to flow the information from macro to micro or some other organizational format. Right now I click on an image and* ***am being bombarded with cryptic information that a designer will most likely not understand,*** *and might also not want to spend time trying to understand. For example, the structural information is crucial for a designer, yet, they might not know what Homology stands for. Great start though, and with a bit more translation and organization (Edward Tufte style) this will be a strong tool for designers to access and learn* (designer). [Bold type used by author].

Constructive feedback like the comment above may help future versions of the StrC to improve in the right direction, and especially to be assessed under user-experience and user-centered design standards. One negative aspect detected by the designer above was also mentioned by one of the scientists: the profusion of "cryptic" information, symbols, and terms created for the StrC around species' profiles and widget options, that are unfamiliar to the realms of both science and design. This should be reviewed in future StrC versions.

A few voices in disagreement or just neutral opinions were still good points to consider for future improvements:

- *Not the most intuitive* (Scientist).
- *Perhaps too graphical (but that's maybe solely a scientist's perspective)* (Scientist).
- *Colour picker is not super obvious* (Designer).
- *Where am I right now? Need a navigation structure* (Designer).

As the comments above show, there were discrepancies among some scientists and designers+. Even participants in the same field had conflicting responses to the StrC, as evidenced from the following comments, both of which are from scientists. One described the overall StrC interface as *"fairly intuitive"* while the other said it was *"not the most intuitive."* Some participants seemed to be trying to assess a final working version of an interface and not a work-in-progress prototype. This issue was also observed for the widgets in particular; ostensibly, the more realistic the prototype the higher the expectations of the user. Yet, such comments are very valuable for future steps of design, development, and the user-experience (UX) testing of the StrC environment.

One response common to both scientists and designers+ was that the majority found the StrC "appealing and intuitive." This can be understood as a "good first impression," one that will invite designers and scientists alike to use a common environment such as the StrC. This is summarized in Fig. 5.27, a visualization done by text-content analysis tools (see p. 233).

(b) The Main Taxonomy

Most of the comments on the main taxonomy were on the positive side, and in some cases displayed signs of excitement (e.g., *"This is great"*—Scientist). Positive comments were either focused on validating the design concept (e.g., *"Beautiful and highly interactive"*—Scientist), or remarking on its effectiveness (e.g., *"Easy to explore and to understand"*—Designer).

Some comments pointed to possible problems in as well as improvements to the taxonomy visualization. For instance, an increasing number of species entered into the database could cause congestion at the lower level of the taxonomy visualization: *"The families and species areas may be a bit busy"* (Scientist); individual cells or even entire clusters of cells could become hard to distinguish and nearly impossible to select if the scale of the screen is not modified. A zoom-in-out function may solve this problem: *"The lower level taxonomy boxes are too small to be useful[;] maybe consider zooming in once chosen?"* (Scientist). Unfortunately, modifying the interface's design and programming would exceed the time frame of this academic prototyping study.

One recurrent comment had to do with mixing scientific with common terminology [also in the third comment about question 2.1.2]. Future improvements to the StrC will include a consistent terminology for labeling the different categories of the taxonomy and terms applied to the overall interface and other features.

Comments on the main taxonomy also helped to identify small glitches affecting specific browser versions and/or a specific device's operative system (e.g., some buttons did not react when clicked). There were no major issues reported about the taxonomy functioning (either in survey comments or red layer comments).

Questions about the main taxonomy took an interesting direction starting with the first part of the question on the overall interface environment (about positive first impressions and constructive criticism) and continued with participants contributing suggestions to consolidate the usability of a future full version of the StrC.

(c) The Red Layer for Contributions

Overall, the red layer for contributions was positively considered by participants. However, results collected from participants' exploration of the interface (quantitative data collected from GA tools) and other comments about this survey suggest that the red layer was not the most prevalent element of the exploration. The expectations on this feature for the StrC study were high: scientists using the red layer to contribute to StrC content is an essential concept to enrich the tool and build a community of peer scientists facilitating knowledge about structural colour. Although it was infrequently used in the study, this feature may become more relevant to users with more development in more advanced stages of the StrC. On the one hand, comments from participants validated the appropriateness of the feature:

- *… looks relatively easy to contribute* (Scientist).
- *This was a nice feature* (Scientist).
- *Yes, this could help* [to make contributions] (Scientist).
- *Clear and easy to read* (Scientist).
- *The distinct red overlay separating the 'editing and contributions' section is quite intuitive* (Designer).
- *This is really cool* (Designer).

On the other hand, comments may help to detect problems and anticipate improvements for a more developed version:

- *…I tried to contribute to include instances where the mechanism is not listed. But I found I could not edit these* (Scientist).
- *If there's a way to mock-up / tag where [there] needs [sic] to [be] changes, that would be better* (Scientist).
- *It is maybe a pity the submitted comment/question/etc[.] does not appear on screen after submission. Basically, after submission and clicking on exit, the user can't see his/her comment* (Scientist).
- *…how would I contribute a completely new taxon?* (Scientist).
- *The floating plus signs were a little less intuitive. Maybe as a possibility the section being edited would highlight or be outlined?* (Designer).
- *If you could include a tool to circle or otherwise markup the webpage this might add more functionality* (Designer).

Many of these suggestions are feasible design and programming adjustments. While most participants find the StrC intuitive and easy to use, some comments indicating frustration and some confusion at the level of user-experience are good sources for improvement beyond this academic prototyping version. The overall potential of the feature is promising, and following the suggestions from the study may help to improve it even more.

(d) The Widgets

Positive comments from scientist participants about the widgets were contrasted by a similar number of rather negative comments (to question 2.1.12d). On the one hand, scientists could see the potential of these tools beyond the available mock-up versions (e.g., *"My favourites, widgets look stunning and comprise lots of information"*) or in simple comments (e.g., *"Useful~!"*). On the other hand, some scientists could not experience these tools as they wished:

- *I imagined this will be more useful when the db [database] will be exhaustive.*
- *Too underdeveloped for me to test well.*
- *These were unclear to me and need better explanations and clearer layout.*
- *Wasn't sure what all of them were supposed to do, or what all of the visuals mean?*

As reflected in question 2.1.5, the realistic aspect of the widgets might have created higher expectations in participants willing to explore these tools with real data. These expectations may have made the widgets look underdeveloped. Still, these kinds of comments are useful for highlighting the limitations of mock-up versions to address complexity. One thing was clear: the evolutive disruptions widget seems the most controversial for reasons described earlier in this chapter, as this comment suggests: "*…Definitely nix the evolutive disruptions one."*

In contrast to the scientists, designers+ responded positively to correlated question 2.2.10, about whether the future fully developed versions of the individual widgets would make a big contribution to the StrC. The totality of designers+ participants (100%) agreed that fully developed versions of the widgets would make a big contribution (Fig. 5.18); the designers+ projected the potential of these tools beyond the available mock-up versions.

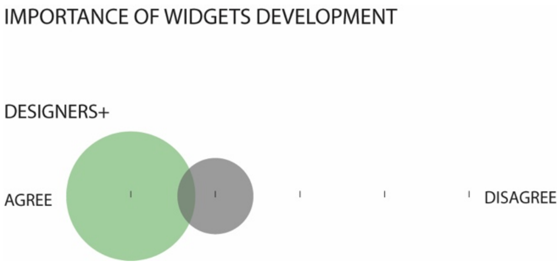


Figure 5.18. Importance of the future development of the widgets (full agreement from designers+ participants).

Additional comments on the individual widgets from designers+ supported the figures above. The following is a selection of those comments divided by widget, and with some highlighted ideas (bold type used by the author):

- Homology:
  - ***This is the jewel of the data for a designer, visual story telling of what the strategy is.*** *Perhaps an option to roll over each item to gain more insight could be helpful....*
  - *Love the visual and colourful interface.* ***It helps to translate the information to a non-scientist.***
- Phylogeny:
  - *Not sure if this information is needed for a designer[;] however, for scientists it probably is very helpful.*
  - *This is really neat[;] I love seeing how everything ties together! Pretty cool.*
  - ***The phylogeny section is quite easy to comprehend[,] which is it's[sic] strength***.
- Research Map:
  - *Location... love it. What about people adding pictures from iNaturalist?*
  - *When I clicked on the 7Vortex map it was not working properly for me. Think this will be cool when fully built up.*
  - ***7Vortex tool is an excellent aid to the platform***. *I would continue to use the greyscale colour theme. Since StrC is about colour, use of greyscale is helpful to separate important information from the less important.*
- Evolutive Disruptions Timeline:
  - *…a game changer. Could we see evolutionary disruption from different kingdoms?*
  - *I wasn't sure what this meant or how to interpret it. The links on the left led me to research paper, but that didn't explain the graphs or what they mean. They look*

really interesting though! I especially like the look of the bottom one.

– *It is very intuitive to be able to notice the different disruptions taking place through the whole timeline. Could this section benefit from more information about what led to certain disruptions or more context?*

To the eyes of designers, the widgets' strength lies in the visual capacity of communication, and not in the accuracy or conceptual appropriateness of the scientific information. This differs from scientists, and it is observed in the responses: consistently high acceptance among designers+ and divided opinions among scientists.

A word cloud was generated as an additional hermeneutic element of analysis of the designers+ comments on the widgets, showing words such as "information," "helpful," and "works" as dominating concepts (Fig. 5.19). It is worth noting that other attributes of the overall StrC environment, such as "intuitive" (see text analysis described in Fig. 5.27), are not mentioned in these comments. This can be interpreted as a disadvantage of the widgets compared to other features and the overall StrC experience. The widgets being not fully developed limited the participants' perception.

Figure 5.19. Word cloud of all terms collected from additional comments to question 2.2.10. The size of the words corresponds to the number of times that word was mentioned.

(e) The Relevance of the Colour Picker

Scientists and designers+ were asked whether they agreed or disagreed with the statement *The colour picker shortcut is a relevant function, useful for grouping and displaying items, and* *to have a sense of what is available in the collection.* Most of the participants agreed (64% of scientists, and 100% of designers+), representing three quarters of the total (74%); 13% were neutral (18% of scientists, 0% of designers+), and 13% disagreed (18% of scientists, 0% of designers+). See Fig. 5.20.

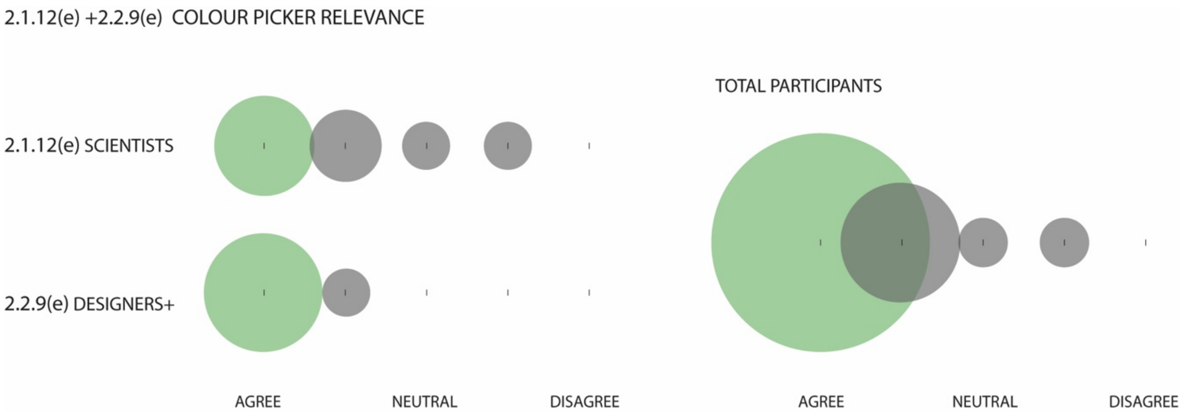


Figure 5.20. Level of agreement on the relevance of the colour picker. Designers+ participants completely agreed about the relevance of the colour picker, while scientists remained more cautious.

These results indicate that the scientists were slightly reluctant to see the colour picker as a relevant function, while designers found it essentially functional. Yet, scientists assumed that the colour picker would be relevant for designers: *"It can be inspiring for designer[s] but not very scientifically relevant. But I would keep it"* (Scientist). A few scientists and the majority of designers found the colour picker both appealing and functional (e.g., *"This was my favourite feature of the site"*—Scientist).

Criticism from scientists and designers+ alike is indeed excellent feedback for further development and enhancement of the picker. For instance, the need to more broadly represent the colour spectrum triggered good ideas such as turning the picker into a slider tool:

- *Can you use* ***a slider across a spectrum*** *to include more continuous spectra? Most spectra are broad* (Scientist) [Bold type used by author]
- [Add] *search by wavelength range, where user picks the upper and lower limits they'd like returned* (Scientist).

– *I wonder if it also could be a slider to allow designers to be more exact with their colour choices?* (Designer).

Scientist also expect to be able to find and classify other aspects of colour complexity, as the following comment suggests:

> *It may be a bit vein [sic] to categorised [sic] species into seven colours [actually eight, if white is considered]. Colour is much more complex than this [given colour picker options]. In addition, what about the species' tissues of [sic] which were made more transparent thanks to micro-/nanostructures? Or integuments[,] the black appearance of which is enhanced by micro-/nanostructures?* (Scientist)

Fine-tuning these colouration mechanisms would be definitely an asset, if not for the colour picker, at least for other parts of the StrC taxonomic information (e.g., in the widgets).

All of the comments above provide relevant suggestions for improving the functionality and enhancing the capabilities of the colour picker. Other comments pointed to the detection of usability design issues relatively simple to adjust, such as improving the navigation sequence to make it switch easily from picking results to starting a new search: *"...once the page changes, I cannot figure out a way to go back"* said one scientist, while another observed that it's *"Hard to find your species again if [you are] using the colour picker as there is no back button."* Other less relevant comments in terms of contributing with suggestions (e.g., several *"love it"* or *"like it"* responses) are still underpinning the direction taken by this idea.

5.1.2.1.13 StrC Helping to Inspire Biomimetic Ideas [Question 2.2.2]

Designers+ participants were asked to agree or disagree with the statement *StrC provides access to scientific information and knowledge in a very effective and intuitive way to inspire biomimetic ideas.* Most designers+ agreed (88%) with this statement, while no one remained neutral, and 12% disagreed (Fig. 5.21).

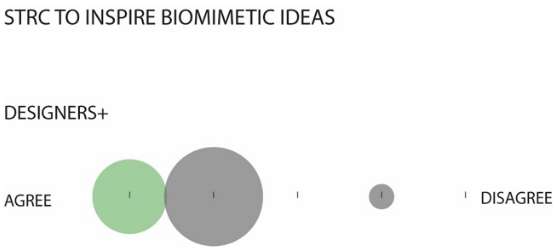


Figure 5.21. Support from participant designers+ on the StrC as a way to access scientific information for biomimetic implementation.

The effectiveness, though, must be contrasted with the input from scientists suggesting improvements to the content of the interface. Designers tend to be biased by the way things appear to be or are communicated (i.e., ergonomic interpretations and affordances of artifacts), while, from a scientific point of view, what is known (based on evidence) subordinates what is perceived. Without scientific validity, what designers may consider effective for biomimetic design could be partially or completely mistaken.

Additional comments from the participant designers+ focused mainly on the design and functionality aspects of the interface, and predictably not on the veracity of the scientific content; for example,*"Great organization and temporal flow of data, one thing that could be improved upon are some legibility issues with small or light text"* and *"Interaction is beautiful and I can see many different visualizations as well."* Some designers+ also pointed to the nature of an academic prototyping process: *"There is [a] learning curve, but it's reasonable"* and *"Looks like it could be a great tool but still a little rough around the edges."* These comments connote that this current version is work in progress.

5.1.2.1.14 StrC Effectiveness to Better Understand Structural Colour and Facilitate Access to Scientific Information (Question 2.2.3)

Designers+ participants were asked to agree or disagree with the statement *StrC provides elements to better understand the concept of structural colour and facilitates access to scientific information on structural colour.* This question had a two-fold goal: it asked designers+ to assess the StrC as a space that facilitates access to scientific information that designers need beforehand for biomimetic projects, and it asked them to use the StrC to learn about structural colour. However this question was asked when designers had little or no knowledge about the subject.

Nonetheless, most designers+ (88%) agreed with the statement, while 12% remained neutral, and none disagreed (Fig. 5.22).

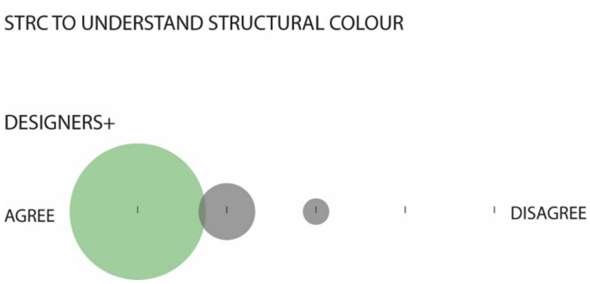


Figure 5.22. Support from participant designers+ on the StrC as a facilitator to better understand structural colour.

A few additional comments addressed the question with very positive reactions, too (e.g.,*"I have already learned new things"*). Besides the StrC features, other sections of the interface seemed useful and informative to designers, as evidenced by this comment: *"The information on structural colour in the 'About' section was really helpful. As a person without much knowledge about this field, such information makes the platform accessible to not just specialists in the field but to all researchers."* The "About" section of the StrC may change in the future, after the study, and may play a different role; it may include access to more educational information on structural colour.

5.1.2.1.15 StrC Encourages Doing More Research on the Subject of Structural Colour (Question 2.2.4)

Designers+ participants were asked to agree or disagree with the statement *After experimenting with StrC I am interested (or more interested) in doing more research on the subject of structural colour.* This statement produced a wide range of responses, predominantly positive: 62% of designers+ participants agreed with the statement, 13% remained neutral, and 25% disagreed (Fig. 5.23). The distribution of these responses along the spectrum of opinions also correlates with the variety of backgrounds and areas of practice of these participants (see demographic details in question 1.2, section 2.2), some of them more and others less familiar with the subject of structural colour. This distribution contrasts with the responses from the scientist counterparts, to whom the subject of structural colour is more familiar.

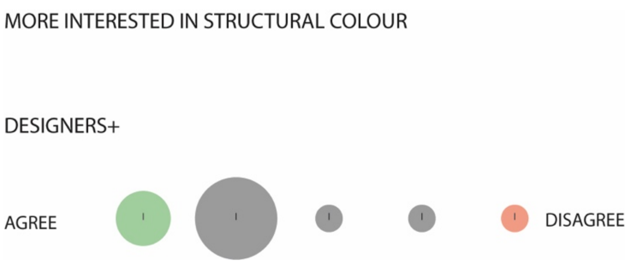


Figure 5.23. Distribution of opinions from participant designers+ on doing more research on structural colour after exploring the StrC.

There is agreement, predominantly. Only a few responses were more elusive or showing a lack of interest. The number of additional comments was also low in comparisson to responses to other questions in the survey (e.g., *"I do not use structural colour so much, but when need it I will know where to go"*). The small number of comments in response to this question is likely a reflection of the limited knowledge that the designers+ had on the subject—especially the current limited applications in design, as can be seen from their demographic responses to question 1.8. This can also be seen as a sign of the gap between disciplinary realms, where scientific information may look too complex to non-scientific audiences.

5.1.2.1.16 StrC Stimulates Seeking New Biomimetic Applications (Question 2.2.5)

Designers+ participants were asked to agree or disagree with the statement *After experimenting with StrC I am interested (or more interested) in finding new biomimetic applications for structural colour.* Three-quarters (75%) them agreed with this statement, while

12.5% remained neutral, and 12.5% disagreed. No additional comments were added to this question (Fig. 5.24). The higher response rate to this questions suggests that designers+ privilege applications to research on the subject but that both remain important to that group. This idea correlates with designers' demographic responses to question 1.7. The StrC may play a role not only in connecting science research with design implementation and its actors, but also to motivate designers to connect realms from research, to conceptualization, to applications.

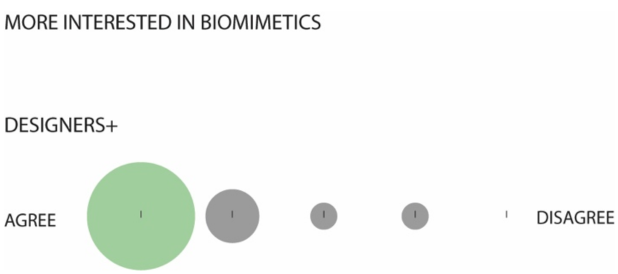


Figure 5.24. Interest in biomimemic applications after exploring the StrC. The bubble-line illustrates how the majority (the first two bubbles represent 75% of designers+ participants) thinks their interest in structural colour biomimetic applications has increased.

5.1.2.2 Responses Collected Through the Feedback Red Layer

The application programming interface (API) back-end collected 14 responses from engagement with the red layer feature during the 8 weeks of the study. These responses were transferred in a spreadsheet for analysis and future follow-up purposes (Fig. 5.25). A few responses received from participants were only as a way of testing the features. It was expected that the red layer function could be a key indicator of engagement and in particular that could initiate discussions and an inviting space for scientific contributions. However, during the study the function received little use compared to other StrC features, which suggests that this space, while promising and well-ranked by participants, had a marginal effect on the results. Design improvements could increase the function's visibility, interactivity, and effectiveness of the red layer, which may increase contributions. However, the limited number of contributions may be due to other factors too, such as the time frame given to participants and their familiarity using the tool. If a community of StrC contributors would be developed, as one scientist suggested in a comment, more regular visits to the StrC would result in a more intensive use of the red layer. Despite the few contributions, responses providing feedback were useful overall, to apply little fixes to the content of the StrC in an academic prototyping fashion. The use of the red layer input to modify and adjust content while conducting research demonstrates the dynamism of this method, a way to quickly send feedback to StrC researchers.

StrC Study RED LAYER API FEEDBACK

LOG	Feedback type:	Feedback location:	Email:	Feedback:	Feedback Meta:	Feedback link:	Feedback file:	Resolution
addition2019-01-16 18:40:08.172760+00:00	Adition	icicle		Tarantulas also have 1D (multilayer) interference mechanism.	Animals			fixed ✔
correction2019-01-16 18:41:12.437356+00:00	Correction	icicle		The SEM images are incorrect (I think it is currently showing bird feather barbs and barbules).	Animals			This comments might be for the homology widget simulation
correction2019-01-22 20:48:32.854014+00:00	Correction	icicle		All "Phylogeny" and "Homology" tabs seem to link back to the dogbane beetle	Animals			Due to simulation Future discussion
suggestion2019-01-28 05:07:21.898393+00:00	Suggestion	icicle		How the category is narrowed down works well, not so sure about the applied colour on these category under the kingdom.	Animals			
suggestion2019-01-28 05:14:47.121630+00:00	Suggestion	mechanism		I am not sure whether this is clickable.	166			Good point to test affordances in UX study
endorsement2019-02-06 17:47:59.691481+00:00	endorsement	icicle		##################################### #	Fungi			
endorsement2019-02-06 17:50:39.722512+00:00	endorsement	research_map		bubbles disengage from the map. ie: I pan around and when I move the map stays the	undefined			
suggestion2019-02-07 03:03:25.134626+00:00	Suggestion	word-cloud		Maybe this area could say "show full publication list"	126			Doable
endorsement2019-02-07 03:04:30.192372+00:00	endorsement	picture		Cool photo! vaguely N. America. Should be able to be	44			

Figure 5.25. Spreadsheet for analysis and follow-up of red layer input. The column in red contains notes and actions taken by the researcher as part of the academic prototyping process.

5.1.2.2.1 Components of the Red Layer Function

The red layer function offers nine possibilities for users to contribute: Endorsements, Suggestions, Corrections, Additions, Conflicts, Questions, Email to be contacted, Links, and Uploading files. The input collected is summarized as follows:

- **Endorsements**
  - Taxonomy: *It would be helpful to put at least the very fine level of detail (specific species) in alphabetical order by [L]atin name. If there is a logic to the order of species here, I am not sure what it is and as the database grows it may become very difficult to find a specific species of interest.*

This is a good idea to improve the taxonomic search, especially if scalability is considered. The current logic of the order is chronologic, by entry date/time, but changing the order to alphabetical or even making this an option for the user to choose is completely feasible.

- Research Map: *When I click in the research map the bubbles disengage from the map. [i.e.,] I pan around and when I move the map stays the same but I can move the bubbles around, so that they are on top of the ocean or any other continent.*

There is a simple explanation for this problem: the embedded 7Vortex bubbles tool combined with a world map has limitations at this prototyping stage. While this feature works well in the 7Vortex environment, the tool is difficult to adapt to the StrC environment for now. An adjustment in the coding may correct this problem in the future.

- **Suggestions**

- Taxonomy: "*How the category is narrowed down works well. [N]ot so sure about the applied colour on these categor[ies] under the kingdom."*

The taxonomy colour palette was carefully thought out to be differentiated from other colours in the StrC environment (e.g., the colour picker). There is no other content reason for the colours chosen; however, the taxonomy colour palette can be reviewed and easily changed if it leads to communication problems.

- Mechanism: *"I am not sure whether this is clickable."*

Many visual elements in the species profiles and widgets look clickable but they are not. In a very interactive and supposedly intuitive environment, it is important to avoid this kind of confusion. An entire assessment on the affordances of StrC functions could be done in the future, especially as part of usability studies.

- Word cloud: "*Maybe this area could say 'show full publication list.'"*

This is an interesting and feasible suggestion. It is also a good example of what can be done during an academic prototyping process.

– Mechanism (in regards to the *Scarlet Tanager*): *"Red here is probably not a structural colour. Likely produced by carotenoid pigments."*

This comment was made by one of the world's top scientists on structural colour. It is not only a possible amendment, but also a good example of ongoing scientific discussions about structural colour mechanisms. The terms "probably" and "likely" and the submission under "suggestions" set a cautious tone around the subject.

- **Corrections**

– Widgets: *"The SEM images are incorrect (I think it is currently showing bird feather barbs and barbules)." "All 'Phylogeny' and 'Homology' tabs seem to link back to the dogbane beetle."*

These two corrections were suggested under the assumption that the SEM imagery shown in the widgets was real data and not simulations. With the development of the real widgets these issues will no longer be a concern.

– Geography –*"They're in South America. [The g]raph is showing vaguely N. America. [It s]hould be able to be much more precise than just which hemisphere."*

This is also a matter of fully developing all the functions and tools in the future, but the suggestion of being much more precise is relevant and it can be done by adopting geolocation maps similar to the ones used in iNaturalist.org (one of the listed repositories of the StrC in the future).

- **Additions**

– Species: *"Tarantulas also have [a] 1D (multilayer) interference mechanism."*

Another of the world's top scientists on structural colour (and an expert in the tarantula species mentioned) suggested this addition. In terms of the academic prototyping content, it is an easy detail to fix. However, missing on this detail is another link to the underlying discussion around structural colour definitions. It has been suggested that many mechanisms (1D, 2D, 3D) can be found in diverse combinations across nature, and some combinations and variations may yet remain unknown.

- **Conflicts**

  – Search: *"Morphos don't come up when I search for 'butterfly' (Really none do except Julia)."*

This participant discovered a glitch in the still-underdeveloped search engine. These issues should be fixed in a future fully functional prototype.

- **Emails Provided**

Only one participant offered an email address for future contact. This was related to one addition and one correction. In a future StrC environment, a system for user registration may make it unnecessary to collect email addresses from contributors already registered in the StrC.

- **Questions**

  No questions asked.

- **Links Provided to Suggest Websites**

  None.

- **Files Provided (Articles, Photographs, etc.)**

  None.

Although these last three options were not used, they are important to keep for a future fully developed red layer.

The red layer function overall is a promising and effective tool, perhaps not so much for collecting useful data for analysis in this study, but for future use in advanced stages of the StrC interface, when scientists' activity increases following an exhaustive population of the database. A very active red layer function will demand an active StrC community, capable of evaluating and curating contributions in peer-reviewing fashion, as well as a red layer team of researchers and developers behind the scenes, to execute updates and changes in the back-end.

5.1.2.3 Thoughts on Structural Colour Collected From Additional Interviews

After the survey responses were collected, eight scientists[92] were selected from all of the participants and contacted to answer a few additional questions on areas of discussion with potential for the StrC. The content and outcomes of these interviews built upon the possibility that StrC can play a role as a tool for research and as a space to bridge disciplinary differences and facilitate the exchange of ideas. Four scientists participated in these additional interviews, which were entirely done by email exchange. The resulting responses and discussions are reported on the following pages.

- **Interview Question 1.** *Full agreement on the number, variations, and/or combinations of structural colour mechanisms in nature is still under scientific debate. In your view, what are the constraints or limitations that science faces to arrive to at a clear classification and categorization of structural colour?*

All the interviewed participants agreed that this is an enduring debate, a long-term or even a permanently open debate, if not about the particularities of the mechanisms, at least about the semantics that define these mechanisms. However, all of the issues that prevent this debate from being resolved in a way that ensures conclusive classification, variations and/or combinations of structural colour mechanisms are solvable issues.

One of the comments evidences the anthropocentric disciplinary fragmentation described in the literature review in Chapter 2. This kind of fragmentation particularly limits the realms of science, as it occurs in nature with “blind alleys” in evolution (Koestler, 1967) as a result of overspecialization: *“There are many different variations, every case differs, you can do grouping*

[92] The selection was made based on the level of knowledge and experience in structural colour research, from information collected from the survey; these scientists are also key authors of scientific articles and members of renowned biophotonic labs.

*but you need someone who is very knowledgeable in the field to do it and **people with skills in only one discipline might struggle**"* [Bold type used by author].

In contrast, transdisciplinary, multidisciplinary, and interdisciplinary spaces proposed by generalist realms like human ecology and biocentered design (Papanek, 1984; Strauss, 1990) may facilitate overcoming this limitation. The following comments suggest ways to address disciplinary differences:

- *…**Better communication across disciplines would probably also help*** [to better survey the degree of variations]. *For example, I imagine that groups working on biomimetics or modeling are less interested in biological variation; they mainly want a starting point to then engineer or describe mathematically, and a single observation is sufficient. But it would help the biologists among us if these other disciplines also reported variability when characterizing new structures.* [Bold type used by author]
- *I think that issue is more due to the multidisciplinarity of the field. For instance, in pigmentary colours, some fields have different classifications for pigments and oxides. For physicists, they are all pigments. I think that by communicating among researchers from different fields, an agreement could be found. If there were a kind of "Structural colour/natural photonic society," such an institution could easily establish a commonly accepted nomenclature. However, do we really need such a society? I am not so sure.*

The StrC may create synergies between disciplines to avoid the results of excessive fragmentation and overspecialization, and to address communication issues that could create consent on, for instance, a commonly accepted structural colour nomenclature of mechanisms and materials variations.

The comment below suggests that limitations may be due to the role that human communication plays in achieving scientific agreement:

> *Personally, I don't think there's a debate on the "mechanisms" per se[;] more often than not**, the debate is on the definition of terminologies, hence semantics in nature.** This happens to every field[;] therefore it is not unique to structural colour research. Hence, I would say **the constraints and limitations lie in the ways we humans use to communicate ideas,** whether in the form of languages or mathematical formula. There is no way (that humans currently know) can capture the essence of nature completely and faithfully without any compromisation [sic]and trade-off for one. And knowledge or ideas cannot be exchanged 100% loyal from person to person as well. Hence the quote: "I*

know you think you understand what you thought I said, but I am not sure if you realize that what you heard is not what I meant." (Alan Greenspan) [Bold type used by author]

The central point of the debate, if there is one, may pertain to the variations of mechanisms and materials that are not frequently studied. Better surveys may lead to a better categorization of structures and better understanding of structural colour at the molecular and genetic level, and may facilitate methods of measurement to be less time consuming and expensive:

> *I think that variation especially is under-studied. There are quite a lot of papers that describe the optical properties of a biological structure, but often from only one individual, or even only one unit (scale, feather, cross-section, etc) within that individual, without reporting variance in the structure's dimensions. Better surveys of the degree of variation will be useful for several reasons: First, they will help clarify how best to categorize structures. Second, variation is very useful for dissecting the molecular, developmental, and genetic bases of any trait, including structural colours. It would help if it were less time-intensive / expensive to measure nanostructures' high-throughput or in vivo with EM.*[93]

Some scientists are inclined to establish an open debate on the scientific nuances of structural colour, while others maintain that knowledge may be settled and that it is only a matter of semantics and human communication rather than a scientific debate. Independently of these two positions, the StrC may create synergies between scientific realms to reduce fragmentation of ideas, solve communication gaps, and ultimately help to create consent on a basic nomenclature.

- **Interview Question 2.** *How relevant is it to identify and classify structural colour cases by function (e.g., crypsis, aposematism, mating, etc.) rather than, for instance, by wave length or colour hues?*

All the responses from scientists have a common theme: while classifying by function is challenging, it may not be a revealing source of information for participants. Still, classifying structural colour cases by human applications (as it is presented in AskNature.org) and by human perception (as offered by the StrC colour picker) may be practical:

> *It's difficult to identify (figure out) the biological functions of colours (they are likely to have more than one function depending on the context)[;] therefore, I don't think it's*

[93] Electromagnetic nanostructures.

necessary or relevant to me personally. Categoriz[ing] them through possible human applications could be useful though.

As the comment above suggests, one of the possible additions to a future StrC version is to include a formal section of case studies, products, and experimental materials being developed or applied.

By expanding some of its sections and features, and facilitating tools that allow researchers to make connections, the StrC can also ignite thoughtful discussions and new research questions on the function and purpose of structural colouration:

> *I think it's a nice introductory resource for a database like StrC to allow searches by function, and could be helpful for exploring the topic. I predict that any given function, such as crypsis, could be accomplished with many different wavelengths (i.e., green for organisms living on plants, black or mottled in other situations, etc) and also many different types of structures. In other words, I do not expect robust trends to emerge. There are also colours that are multifunctional, or pure evolutionary coincidence (non-functional), or that evolved historically for some purpose that is currently obsolete. It's also really important to emphasize that function has to be rigorously tested... just because a colour occurs in only one sex, for instance, does not prove that the colour is for mating display. Establishing a colour's function requires testing behavior, visual perception, and/or survivorship, and often we infer a possible function without experimental proof.* ***If StrC attributes function to any structures, it also needs to communicate the degree of uncertainty and cite references.*** [Bold type used by author]

Contradicting many responses from the survey in favour of an enhanced colour picker version—which could include a wavelength scale in addition to simplistic colour hue options—the following comment adds a good point for reflection before making any content and design decision on completing or improving the interface:

> *By wavelength seems a bit pointless since several wavelength[s] could be[,] for instance[,] reflected by a single structure and the interaction is often more complex than a single-wavelength phenomenon. By colour hues, why not but it could be a bit simplistic. By function seems relevant but sometimes several functions are involved or most of the time, they are unknown.*

It is evident that the best way to address these limitations is by implementing a combination of multiple methods and ways for grouping and analyzing structural colour cases that allow users to identify what is significant from the findings. The StrC widget concepts were created with this idea in mind, and in this sense (also supported by the responses to the survey) it seems very innovative to the eyes of scientists, as this comment suggests: *"In my opinion not much has ever been organised very differently."*

- **Interview Question 3.** *Is it possible to detect structural colour convergences (e.g., similar mechanism for a similar function) across species from different kingdoms, different ecosystems and geolocations? Would this be relevant to better understand structural colour purposes and possibilities for implementation?*

Again, reticence on any claim or speculation on scientific discussions like this seems to be a common ground. Empirical skepticism is a "rule of thumb" in science, and comments in response to this question are good examples of this: *"There will always be hypotheses like these, but the difficult part is to experimentally test them. So the short answer from me is No, not an easy thing to do."*

There is a key part of the StrC that provokes these kinds of discussions, revealing new thoughts or confirming old ones, and even allowing for the possibility of sharing available literature to back up new findings:

- *Maybe [it is possible to detect structural colour convergences…]. If the function is "circularly polarized light" or "terrestrial transparency" —in other words, an optical function—then I think very different species probably would have mechanistic similarities. If the function is "camouflage," or another ecological/behavioral function, then definitely no, I don't expect convergence.*
- *I suppose some trends could be found but I anticipate many exceptions.*
- *Yes, it think it can be useful and there are papers on this.*

Responses to the second part of the question, *Would this be relevant to better understand structural colour purposes and possibilities for implementation,* reveal once again a lack of a consistent view or agreement across scientists. On one side there are afirmative responses: *"Yes, it could. But again, I'm pretty sure there will be exceptions and unknown behaviour,"* and on the other negative responses:

> *No. From the perspective of an ecological/evolutionary biologist, a trait could have a function, but the said trait would not have a purpose (because a purpose has the*

connotation of a higher level intention). Human application (possibilites for implementation —> purposeful) is not necessarily to be associated with a trait's biological function (—> unplanned).

According to the claims in the last comment, human purpose opposes nature's purpose. Another way to put this is that "nature's design solutions" are "unplanned," while human solutions are planned. Thus, the etymological discussion in the background is "purposeful" versus "useful." Human ingenuity is purposeful, nature can be simply useful. This provides an interesting opportunity to confront the philosophical implications of anthropocentrism on biocentered thinking. In Chapter 2 this was reflected under Aristotle's claim, "Nature does nothing uselessly," but this premise still connotates a purpose in nature. Following this reasoning, one of the initial questions introduced in the literature review was "*What is the purpose of colour in life forms?"* Assuming that there is no purpose (because it is "just nature" and not a "higher level intention") seems to fall into an inescapable anthropocentric preconception.

- **Interview Question 4.** *Can you offer a hypothesis or a theory on why blue pigment is rare in nature, and blue structural colour so abundant in comparison? Would this be a clue to understand the origin and evolution of the structural colour phenomenon?*

Achieving blue in nature seems to be one of the most interesting topics to investigate, given the scarce pigmentation resources that reflect that portion of visible light from surfaces, and the apparently abundant blue colouration present in coherent and incoherent structural colour. According to scientists, not one but a number of options can be offered to hypothesize about blue structural versus blue pigment colours. Many of these options are supported by available literature on the matter, some mentioned in the comments below. Among the thoughts that scientists offered, some addressed the difficulties that organic pigments have when synthesizing blue:

- *My hypothesis is that "true organic blue pigments" require harsh (unphysiological) conditions to synthesize…*
- *… blue pigment is difficult to biosynthesize for fundamental reasons, like there are fewer molecular solutions that could work than for other pigment wavelengths, based*

on immutable properties of light and biochemistry,

- *...a paper by Prof. Serge Berthier*[94] [suggests] *one of the reasons is that blue pigments are quite difficult to extract since they are usually not very soluble,*
- *...from a chemical point of view, nature has not favour[ed] molecules able to absorbed all [sic]wavelengths apart from the "blue ones." That would mean from ca 500 to ca 700 nm, with a peak at 600 nm. In terms of frequencies, this is quite broad, too.*

In contrast, structural blue seems easier to achieve:

- *...for animals with a visual range that includes UV/blue, structural blue is easier to attain (if not the only way).*
- *Absorbing a few wavelengths at 530 nm (i.e., green) is probably easier in terms of resonances and would give rise to a purplish colour. The "blue" colours are also the most energetic ones. Nature tends to absorb UV. "Blues" are next to that range and may "suffer" from that.*

Additional thoughts addressed other interesting theories to explain the phenomenon:

... it's sort of a snowball phenomenon based on evolutionary history, that could have turned out differently in an alternate world if a few early events played out differently. Red, brown, and/or black pigments arose early in the evolution of major clades of animals, as did materials like keratin and chitin that cause reflectance. Since then, when organisms encounter circumstances that favor blue wavelengths, it's easier to evolve blue structurally simply because the components are already in their ancestral genomic tool kit, while a biosynthetic pathway for blue pigment isn't. It's just the difference between starting from scratch versus starting from a partial solution.

The question of abundant structural blue can be reversed to inquire about the opposite phenomenon in other colour hues, for instance the scarcity of structural red:

For the reciprocal thought experiment, why aren't there more structural reds? Are they just underreported? Is it a similar phenomenon [to the scarcity of pigmentary blue], where red pigments are common mainly because they're ancestrally available?[95]

The abundance of structural blue, or any colour, can be also a bias due to perception and the ways we measure that abundance:

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[94] Prof. Serge Berthier is a physicist from Sorbonne Université (France), and an expert on photonic structures of insects. He has published several articles and books on the matter. This author was not included in the original literature review for this dissertation or invited to the StrC study; however, his input is a very good addition for the future of the StrC project.

[95] The participants offered a reference on *"some limitations making it difficult to generate a good red with colloidal glasses"*; https://doi.org/10.1103/PhysRevE.90.062302

> *On one hand, the abundance of blue among structural colours may be overstated (…) since that colour stands out with respect to green, for instance. That is why blue Morpho butterflies were extensively studied. However, there are surely as many examples of green colours: many insects or butterfly species are green. On the other hand, it may be totally justified if by "abundance" we do not assume the number of structures or the number of systems (species for living organisms) but their occurrences. The sky is blue (with day light and without clouds). It is everywhere. I suppose this could justify to say "structural blue is more abundant than structural green." Is a chosen colour really so abundant? I suppose that depends on the quantification method.*

This relativeness can be associated with a general perception on the phenomenon of colour: *"... blue (and all other colours) is just a human perception. In a sense, there is actually no such a thing as 'the blue colour'"* (scientist). In fact, we could say, there is not such [a] *thing* as "colour" from a material point of view, things are not made of colour; consequently colour is not a *thing* but rather a result or characteristic of things (the portion of light waves reflected from surfaces or interfaces).

Mapping colours in the visible light spectrum (e.g., using CIE gamut) may reveal other interesting possibilities to reflect upon, such as further purposes in nature to produce visible hues, or even invisible hues not intended to be seen by the human eye:

> *In terms of CIE coordinates, we can probably say that there is a blue area in this diagram. That area contains virtually an infinity of coordinates. However, there are probably less "blue hues" than hues of other colours such as green (based on the size of these areas, even taking into account MacAdam's ellipses),*[96] *but most colours in nature are probably not developed for the human vision. The "blue hue area" is limited by our own vision. And the separation between the "blue" and the "green" areas is also only due to our vision and our photoreceptors. Many green colour and surface reflecting UV [colours] could have appeared blue with a slightly different visual system.*

The discussion about structural hues in nature can also lead to reflection on similar challenges in the implementation arena: *"I found always interesting the fact that blue LEDs were also the most complicated to produce"* (Scientist). The challenges of man-made technologies to achieve blue

[96] MacAdam's ellipses are areas highlighted from the CIE diagram, which represent all colours that are indistinguishable to the average human eye.

coloration may have commonalities with those challenges observed in nature; interestingly, nature seems to afford good results with more frugal techniques.

Many clues and leads were offered in the comments above. These could inspire an entire section in the StrC environment, dedicated to collecting additional thoughts and to initiating discussions.

To the second part of the question [*Would this be a clue to understand structural colour?*], scientists agreed in that conversations on origins and evolution take the scientific discussion to a deeper level, and cannot be reduced to only one aspect (colour) of what we can observe in nature. To some scientists, the origin of structural colour is probably a matter of chance: *"Probably not* [a clue to understand structural colour]. *The origin of structural colour is probably to be accidental/coincidental. Context is very important when considering evolution, a single route of evolution for all structural colours is probably impractical"* (Scientist).

While this scientific discussion is relevant and interesting, the opportunity for the StrC to contribute to new a ground (i.e., connecting this phenomenon of blue with a deeper undertanding of structural colour phenomenon like the second part of the questions suggests) seems unlikely. Nevertheless, simply hosting this kind of discussion is worthwhile in the context of the research question and the idea of building a future "StrC community" and should be encouraged. The collection of thoughts from the interviews is proof of this.

5.2 Summary of Findings From Data Collection

As mentioned in Chapter 4, specific components of the StrC were designed to detect underlying behavioral and conceptual findings. The following is a list of assumptions from Chapter 4 aligned with the findings from the study in Chapter 5:

- **Assumption 1**
  - **Speculation:** *The number of contributions and feedback entered by scientists to the*

red layer function may suggest engagement in communicating scientific knowledge through StrC as a tool for research.

  – **Findings:** The red layer is a promising StrC feature, well rated by survey participants. However, this function was used very little compared to other StrC features, and as such it offered a marginal effect on the study results, and cannot yet be taken as a measure of engagement.

- **Assumption 2**
  – **Speculation:** *Scientists exploring details of the species profile and widgets may detect opportunities to provide feedback on misunderstanding and misconceptions about structural colour mechanisms and variations.*
  – **Findings:** This conjecture was verified. Evidence from the survey responses and a number of relevant comments from scientists on structural colour mechanisms, materials, and multiple variations of these indicate that scientists found opportunities to discuss and contribute with scientific knowledge to the widgets and other functions of the species profiles.
- **Assumption 3**
  – **Speculation:** *The number of visits to specific StrC sections, or features from scientists compared to designers, may support the idea that some aspects considered trivial for one may be considered vital for the other and vice versa.*
  – **Findings:** Whereas this presumption can be verified as true in particular instances, as suggested by a few comments from both designers+ and scientists, the overall survey results indicate that there are not big differences in valuing StrC sections and features. Responses on ranking StrC features are concurrent.

- **Assumption 4**
  - **Speculation:** *The time spent by scientists interacting with the main taxonomy versus interacting with the collection of photos ordered by colour could be inversely proportional to the time spent by designers interacting with the same features: this may suggest that scientists tend to explore data, while designers tend to explore visual cues. Scientists might find irrelevant a taxonomy grouped by colour hue, while for designers this may appear an essential starting point.*
  - **Findings:** This assumption seems true, from the responses to the survey and additional comments by both designers+ and scientists. The responses of the scientists in particular were evidence that the visual cues were not relevant to them; however they consider these cues vital for designers to understand scientific implications. On the one hand designers+ manifested their comfort and enthusiasm exploring the predominantly visual features of the StrC (i.e., colour picker and widgets in particular). Scientists, on the other hand, manifested more interest in content and considered the visuals nicely done but of little relevance, and even as an "excess" of information.
- **Assumption 5**
  - **Speculation:** *Scientists may follow the guiding points suggested to navigate StrC more rigorously than designers. Some designers may completely ignore these guiding points.*
  - **Findings:** There is no indication that this happened; scientists and designers+ followed the guiding points more or less rigorously in the same way. Some details from scientists' comments though, revealed a higher level of responsiveness and

inquiry on the veracity of content and functionality of tools, while designers almost exclusively focused their comments on the communication and usability aspects of the interface.

- **Assumption 6**
  - **Speculation:** *Collected keywords searched by scientists and designers reveals patterns of coincidence and disparity in the language used to find the same or similar results.*
  - **Findings:** This distinction could not be completely verified by the results from analytics tools. From additional comments to the survey, it can be deduced that scientists used the search engine more frequently and with more accurate terminology than designers+, but there is not conclusive evidence to claim this as an actual trend.
- **Assumption 7**
  - **Speculation:** *The number of interactions and the time spent navigating sections and features with predominantly scientific content suggest signs of engagement from scientists, while revealing some limitations to designers in understanding such content.*
  - **Findings:** This presumption was verified as true, according to the data analyzed not only from analytic quantitative tools but also from the survey's qualitative responses. The level of engagement of scientists was clearly manifested by the patterns revealed by the analytics (e.g., time spent exploring the StrC, sections more visited) and deep reflections and comments that the survey questions inspired on key scientific matters. Comments from designers in particular revealed limitations on understanding scientific content, and the designers readily acknowledged their limitations on proving the validity of the data displayed.

- **Assumption 8**
  - **Speculation:** *The number of discrepancies and conflicts highlighted by scientists from content and concepts included in StrC contrasts with the number and kind of comments that designers make on the same content and concepts. This may support the idea that a communication gap exists due to different disciplinary languages, ways of knowing, and perspectives. If these numbers and preferences show no big differences across participants of both groups, this may suggest reframing the assumption of the "gap," and opening new questions regarding the reasons that prevent the biomimetics of structural colour from evolving to design implementation.*
  - **Findings:** The data collected confirmed that, not only there is an interdisciplinary communication gap between designers and other biomimetic practitioners and scientists, but there are also intradisciplinary (or inter subdisciplinary, e.g., biology, physics and chemistry) gaps openly manifested in the comments, and implicitly presented in the participants' choices. Responses to the survey also suggest how influential these gaps can be to slow down the process of implementation, as well as how relevant tools of research like the StrC could be to address these gaps. Participants suggested adding access to new materials and technologies being developed to enrich the StrC database and facilitate the exploration of design possibilities.
- **Assumption 9**
  - **Speculation:** *The order of steps done by designers exploring the main StrC features versus the order scientists used may reveal some patterns that characterize different ways to observe, understand, and engage with the subject of structural colour.*
  - **Findings:** There was not enough evidence to support this suggestion based on the

quantitative data from analytic tools and on the responses to the survey. The only regular order of navigational events identified that revealed a general pattern (with no discrimination between the kind of participant), was one that corresponded to the order of steps suggested by the guiding points, thus making it invalid as a source of information to measure this claim.

5.3 Summary of Findings Grouped by Areas of Interest

The following list summarizes the main points suggested from findings, grouped in five areas of interest: applications, potential scientific discussions, inter and intra disciplinary synergies, limitations, and key suggestions (Table 5.01).

- **Applications**
  - Industries with potential to apply or ones that are currently applying structural colour (in order of relevance according to study results): Textile, Paint, Electronic, Printing, Signaling and Communication, Biosensing, Dynamic Colour, Smart Cities (colour indicators), Marketing, Building materials, and Camouflage.
  - Iridescence disadvantages: it may bias the way we look at and the attention we pay to some colours; controlling iridescence makes it possible to produce stable structural hues.
  - The StrC could include a categorization of colour through possible human applications; linking designers to biomimetic applications seems to add a stimulus to investigate structural colour. The StrC may play a role not only in connecting science research with design implementation and its actors, but also in motivating designers to connect realms from investigation to conceptualization and implementation.
- **Potential scientific discussions identified**
  - Evolutionary aspects of species with structural colour
  - Agreement on structures, variations and combinations of structural colour mechanisms
  - Functions associated with structural colouration: crypsis, aposematism, mating, etc., e.g., aposematism can be associated with short wavelength hues (blues to ultraviolet).
  - Identifying trends of convergence across species from different kingdoms, different ecosystems and geolocations, based on suggested literature
  - Different hypotheses, theories, and biases on the abundance of blue structural colour compared to the scarcity of other structural hues

Table 5.01

Study Participants' Suggestions for Improving StrC Features

Generalities	Main Taxonomy	Species Page	Colour Picker	Red Layer	Widgets	Research Map
Emphasize possible scientific debates on mechanisms and materials, to find technical and/or semantic agreements	Zooming feature for lower categories and species levels of the main taxonomy visualization	Access different spectra from the same species (given that different conditions yield different information)	Enhance the colour picker into a slider	Enhance to ease ways of contribution	Add additional imagery: TEM and spectral; and scale bars to TEM and SEM	Resolve the issue to fix the embedded Research Map to 7Vortex application
Create a new section with biomimetic materials attempts, based on available literature; facilitating scientists to find designers/enginneers	Consolidate terminology, avoid the mix of taxonomic and commonly named groups (e.g., Amphibia and Fish (instead of Actinopterygii)	Link 'possible functions' or 'suggested functions' to available literature	Include variables of wavelenght, structural colour mechanisms and materials	Allowing users to save and edit their contributions	Add CIE mapping: hue range possitioning, RGB and CMYK equivalents; MacAdam's ellipses of indistinguishable colours to the human eye	Enhance ways to find researchers by type of structures investigated, by regions, and link to the literature section
'Talk' to other taxonomy databases (future repositories), and be self-correcting		Symplify and reducing the use of symbols. Integrate the lower panel symbol key (legends in the species profile pages) with the center panel	Allow the user to pick the upper and lower limits they would like returned		Replace Evolutionary Disruptions widget by enhancing Phylogeny and Homology widgets to discuss evolutionary convergence of structures	
Enhance communication and discussion tools (e.g., adding chat function, forum, applications such as Slack, etc.)		Consider replacing (or combining) the colour hue key symbols by an accurate wavelenght value	Add structural black hue		Trace photonic structure evolution better with more attention to biological variation in the structures between species or genera in Homology	
Allow users to step back at any point of navigation, and save entire navigation paths		Improve the magnified view in species profile; add legends for the icon/label/things too			Change the name of the widget from "Homology"' to "Convergences"'	
		Include light polarisation effects in species sensible to it			Add reflectance spectra (from metadata) to colour hue assignments to the Convergences [Homology] widget	
		Make clear that the icons on the left side of species profiles match up with the qualities on the right side			Add lighting conditions, angle, objective lens, smoothing and other processing, reference spectra, etc. to the Convergences [Homology] widget	
		When available, collect meta data about specimens (e.g., Where was it collected and when? Is it an old museum specimen? Was it farmed? Did the researchers only look at one individual? etc.)			Add a rollover option to each item in widgets to gain more insight	
		Enhance the geography function with more details, including habitat, elevation, exact range, exact location of specific specimens whose photonic structures were characterized, etc.				

- **Inter and intra disciplinary synergies: science-science, science-design and design-science,**
  - StrC as a tool for research
  - Other possibilities for the StrC to facilitate connections
- **Limitations of the StrC**
  - ‘Conceptual limitations (of scientific content)
  - Tool limitations (of academic prototyping, user experience)
  - Disciplinary language and literacy barriers
- **Key suggestions to improve StrC features**
  - Enhance the colour picker into the slider, and include variables of wavelength, and structural colour mechanisms and materials. Allow users to pick the upper and lower limits they would like returned. Add structural black hue.
  - Emphasize possible scientific debates on mechanisms and materials, to find technical and/or semantic agreements.
  - Access different spectra from the same species (given that different conditions yield different information).
  - Link “possible functions” or “suggested functions” to available literature.
  - Create a new section about biomimetic materials under development, based on available literature; facilitate scientists to find designers/engineers.
  - Add additional imagery (e.g., more TEM and spectral) and scale bars to TEM and SEM.
  - Add CIE mapping that includes: hue range positioning, RGB and CMYK equivalents, and MacAdam’s ellipses of indistinguishable colours to the human eye.
  - Create a zooming feature for lower categories and species levels of the main taxonomy visualization.
  - Enhance the red layer to ease ways of contribution, which will allow users to save and edit their contributions.
  - “Talk” to other taxonomy databases (future repositories), and be self-correcting.
  - Consolidate terminology, avoid the mix of taxonomic and commonly named groups (e.g., Amphibia and Fish instead of Actinopterygii).
  - Enhance communication and discussion tools (e.g., adding chat function, forum, applications such as Slack, etc.).
  - Simplify and reduce the use of symbols. Integrate the lower panel symbol key (legends in the species profile pages) with the center panel.

- Consider replacing (or combining) the colour hue key symbols by an accurate wavelength value.
- Improve the magnified view in the species profile; add legends for the icon/label/things, too.
- Include light polarization effects in species sensitive to it.
- Make clear that the icons on the left side of species profiles match up with the qualities on the right side.
- When available, collect metadata about specimens (e.g., Where was it collected and when? Is it an old museum specimen? Was it farmed? Did the researchers only look at one individual?).
- Enhance the geography function with more details, including habitat, elevation, exact range, exact location of specific specimens whose photonic structures were characterized, et cetera.
- Allow the user to step back at any point of navigation, and save entire navigation paths.
- Replace the Evolutionary Disruptions widget by enhancing the Phylogeny and Homology widgets to discuss the evolutionary convergence of structures. Trace the photonic structure evolution better with more attention to biological variation in the structures between species or genera.
- Change the name of the widget from Homology to "Convergences"
- Add reflectance spectra (from metadata) to colour hue assignments to the Convergences (Homology) widget.
- Add lighting conditions, angle, objective lens, smoothing and other processing, reference spectra, etc. to the Convergences (Homology) widget.
- Add a rollover option to each item in widgets to gain more insight.
- Resolve the issue to embed the Research Map from the 7Vortex app. Enhance ways to find researchers by type of structures investigated, by regions, and by linking to the literature section.

5.4 Connotations From Enrollment Figures

As described in Section 5.1, 31 participants accessed the study (submitted the consent form, read the guidelines, and accessed the StrC interface). However, only 19 of those participants filled out the survey at the end of the experience (even after several reminders inviting them to complete their participation). This is about 61% of participants. Part of the remaining 39% who did not engage in further feedback might have intended to continue, but eventually they could not find the time to do so (indeed, the researcher received a number of regret messages post-study). It can be speculated that, for others, the motivation to continue after navigating the StrC was not high enough. It is worth remembering that all participants invited were in one way or another interested in structural colour and/or biomimetic design innovation. The lack of interest in the StrC cannot confidently be linked to initial assumptions on the existence of disciplinary communication gaps, thus such findings cannot be taken as concrete evidence.

The last part of the study included email exchange interviews. Eight scientists were invited, four (50%) of whom responded to the interview in time. The selection was made based on the level of knowledge and experience in structural colour research, information that had been collected from the survey. These scientists are also key authors of scientific articles and members of renowned biophotonic labs. While 50% of the scientists contacted could not commit, the other 50% showed a high level of commitment responding to the interviews with thoughtful contributions to this research.

5.5 Overall Entangled Relationships

From the whole experience of participants exploring the StrC environment and providing feedback, entangled relationships (Hodder, 2014) could be identified, either favouring or disfavouring the main features of the interface. The positive response to the StrC as a tool for research and for bridging intra and interdisciplinary gaps is clearly manifested in the results of the study. Fig. 5.26 shows a prevailing number of “green bubbles” (positive responses to the StrC) in relation to the grey (neutral responses) and red (negative responses), of which there are fewer. This general consensus does not minimize the vast challenge that developing a full version of the StrC may entail, but it is an indication of the overall positive prospect of the StrC as a tool for research.

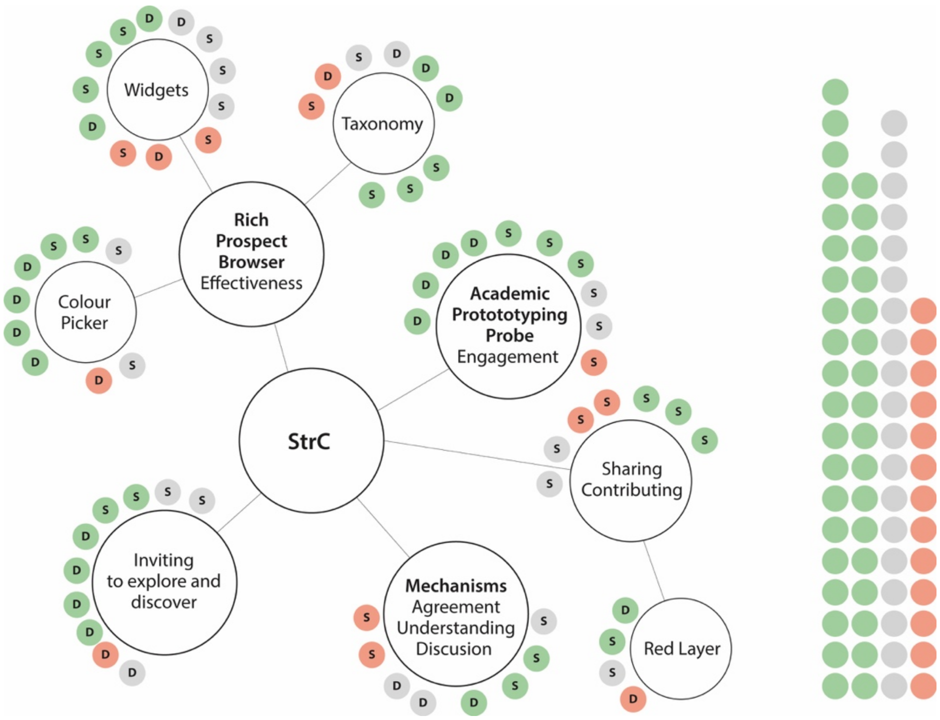

Figure 5.26. "Ecosystem" diagram as an interpretation of entangled relationships in the StrC environment. These relationships are grouped by the features, methods, and purposes involved in the StrC and measured by this study, where the big bubbles represent the structure of the system, and the small represent the individual responses from participants (S=scientist; D=designer+) positive (green), negative (red) or neutral (gray) about the main StrC features. The number of green bubbles surpasses the gray and red bubbles as shown in the side bars.

5.6 Text Analysis of StrC Perception

A hermeneutic interpretation of keywords collected from participants' responses to the open-ended questions in the survey can offer interesting visual results for analysis. Using a bubble-lines tool to read and visualize these responses, it was possible to identify and quantify the dominant words at the two ends of the spectrum between the positive and negative aspects of the overall StrC features. The bubble-lines visualization shown in Fig. 5.27 counted and quantified these repetitions. On one side are the positive connotative keywords (intuitive, appealing, nice, clear, great, and good) and on the other are the negative connotative keywords (unclear, confusing, not, wouldn't, couldn't, and didn't).

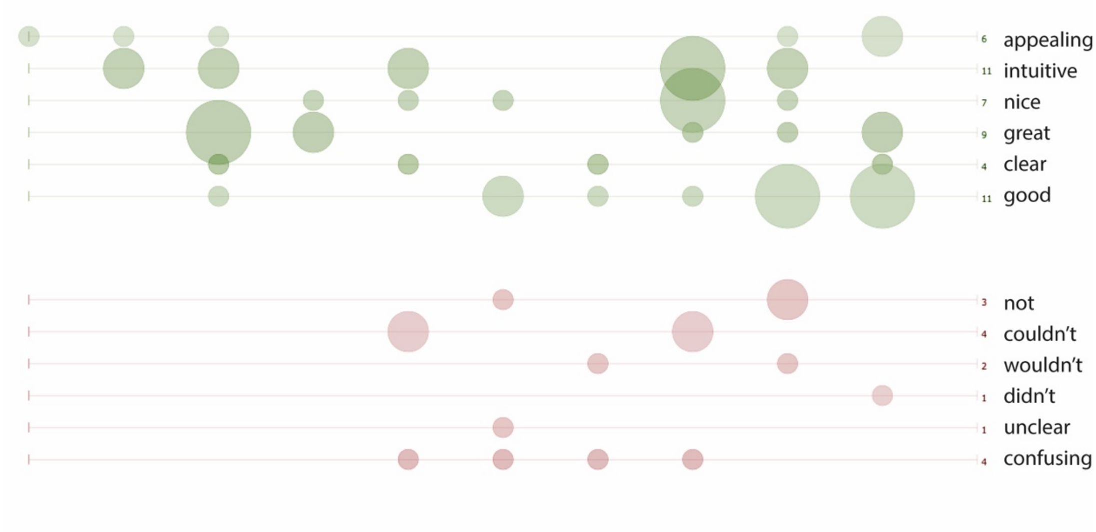

Figure 5.27. Text analysis of StrC perception. This bubble-lines visualization shows all of the participant's comments distributed across all of the survey questions (on top, from left to right). The size of every bubble indicates the number of times this word was used. Both sides of the spectrum are represented; on top, the green bubbles represent the number of times the six listed keywords on the right were mentioned with positive connotations; on the bottom the red bubbles follow the same criteria to show keywords with negative connotations.

Overall, this analysis evidences that positive feedback surpassed negative feedback. However, the comments on the negative side were as relevant and even more useful than the positive input. Pointing at "confusing" issues and "dont's" revealed opportunities for improvement. For the purpose of this research, the positive side covers an important aspect of the research question and validates the use of tools like the StrC to support the assumptions about disciplinary gaps.

5.7 Colour Picker Versus Widgets

From the responses and comments to the questionnaires (questions 2.1.5, 2.1.10, 2.1.11, 2.1.12, and 2.2.9 in particular) and the quantitative data collected by GA, some initial conclusions can be drawn about two main StrC features, the colour picker and the widgets. The relevance of the colour picker and the widgets differs depending on who is doing the analysis: the designers or the scientists. The colour picker is accepted as appealing across participants. However, while designers assigned a more relevant role to this function, scientists suggested it was more aesthetic than functional, yet valuable as a tool for reaching a broad audience. The widgets also seemed attractive to designers and scientists alike, but scientists were more critical about the accuracy, validity, and effectiveness of these tools at conceptual and detail levels. There is a lot of room for improvement in both the picker and widgets. For the widgets, at least, there was an assumption even before using the mock-up versions that there was room for improvement. However, for the colour picker, the findings revealed unexpected opportunities: the colour picker could also function as a colour slider, a structure picker, or even a structure+colour slider. The input collected from participants contributed to the academic prototyping case, and opens a space for dialogue between science and design for the creation of tools for an ecosystem like the StrC.

5.8 A New Section With Biomimetic Materials and Product Attempts Is Needed

One key suggestion from scientists was to connect available knowledge from science to current materials being attempted and applied (see comments to questions 2.1.1 and 2.1.9). Linking the StrC to AskNature.org was intentionally planned as a source to link case studies of biomimetic function and implementation. However, cases of structural colour being developed or researched are not fully covered by AskNature.org or any other database. Including case studies of implementation, and materials and products under development derived from scientific literature (as suggested by participants in question 2.1.1) is a feasible challenge for the StrC. Accessing literature on applications of structural colour in areas of photonics, nano materials, and materials engineering could be part of the next StrC stages on accessing external repositories and library systems, in this case for collecting case studies from the available literature. Similar or identical tools developed for collecting metadata on the science of structural colour could be used to collect metadata on new materials and products applying structural colour. Scientists aware of biomimetic designs, new materials, or technologies being developed, who are seeking structural colour advantages, may initiate or redirect their scientific work to contribute to such ideas.

5.9 Conclusions

This chapter first helped to identify and understand limitations of the design study, the methods used, and the overall limitations of the main subjects—structural colour, biomimetic design, and a biocentered approach—as matters of study.

This research project started with a main assumption, that gaps in communication between scientific disciplines and design disciplines may create limitations in accessing and understanding available scientific data useful for biomimetic design projects. A two-part correlated research question was then formulated: *How can a biocentered design approach to colour help bridge gaps between scientific knowledge and biomimetic design practices? How can available scientific information/knowledge on structural colour be better organized and more accessible to bridge such gaps?* The findings of the study are supporting evidence of this initial assumption, as well as suggesting that research tools like the StrC may be a way to address these gaps, making available scientific information on structural colour more accessible and better organized for designers and biomimietic innovators. These findings also suggested areas of improvement and new challenges to be considered for future development, new angles to the problem, and new questions to ask. The findings also contrasted, reformulated, and even challenged some initial pre-study assumptions. Finally, these findings have informed the reflections that follow in the conclusions in Chapter 6.

CHAPTER 6: CONCLUSIONS

"People can only understand things that relate to things that they already understand."[97]

6.1 Summary

The main goal of this dissertation was to explore a way to bridge the gap between science and the design implementation of structural colour. This work was motivated by the significance of a biocentered design approach to adopt sustainable practices. As the quote that opens this chapter suggests, building a bridge to facilitate understanding between fundamentally distinctive disciplinary realms is a challenge that requires multiple disciplinary strategies to arrive at a common ground both for scientists and designers. In a transformative fashion, this scholarship took nutrients from the realms of human ecology and material culture in ways of knowing and ways of conducting quality research, and from design studies by doing research that involved the creation of new tools (such as the StrC). The postulates of this research also implied a dash of autoethnographic thinking, influenced by a reflective practice approach from design disciplines. An interdisciplinary stance, informed by design, material culture, human ecology, science, and biomimetics, defined the core elements of this project: the need for an extensive multidisciplinary literature review; a multidimensional (and flexible) approach to a methodological standpoint that made it possible to find the right methods, strategies, and tools for the study; and the need to create a customizable mean or *probe* (the StrC rich-prospect browsing interface), to test, support, and justify an exploratory process (academic prototyping). Despite the intense interest in science that the realms of biomimicry and the subject of structural colour in particular demand, this dissertation remains a case of interdisciplinary studies with social sciences characteristics.

[97] From researcher's personal conversation with Jorge Frascara, April 2018.

This dissertation shines the spotlight on the influence that science can have on design thinking. This influence became part of the final message given by the conscious mix of disciplinary realms: learning from nature (through science) to find ways to design with a biocentered approach, bridging the disciplinary gaps between science and design, and in the process, trying to escape the anthropocentric bubble of contemporary design practices. Based on the findings of the study, this research concluded with elements that corroborate the initial assumption—that disciplinary gaps may prevent progress in understanding and implementing structural colour in design projects—and addressed the research question of how to bridge these gaps by introducing tools of research such as the StrC.

This dissertation offered an introduction to the areas of interest involved in this research, the scope and relevance of the subject of study, the purpose and intention of the research question, and the significance of the study. Through an extensive literature review, this dissertation also explored a number of subjects and ideas: the epistemological foundations of a form of interdisciplinary scholarship influenced by the realms of design, material culture, and human ecology; the philosophical foundations that connect the project to sustainability and biocentered thinking; and the area of focus, structural colour, which gave purpose and content to the exploration. The methodological multidimensional approach and multiple method strategy employed introduced academic prototyping and rich-prospect browsing as central concepts to the execution of this research study, among other methods explored. Chapter 4 described the preparation of the StrC study, design, development, materials, and logistics for data collection and analysis.

While working on this dissertation, results from the StrC study provided additional input, new questions, challenges, and ideas for further development as described in the findings chapter

(Chapter 5). This information also served to contextualize the current state of structural colour investigation and implementation across the scientific and the biomimetic design community. Finally, these conclusions serve as a summary of the entire doctoral endeavour, which is the result of almost 6 years of intense work, although always a very enjoyable journey.

The following list summarizes[98] the accomplishments of this doctoral scholarship from incubation to the outcomes of the StrC study:

- Completed course work in Human Ecology subjects, elective subjects (in Science and Design), and two independent studies on Structural Colour.
- Conducted preliminary study on a biocentered approach to colour (HECOL 562).
- Completed Comprehensive Exam and the four associated papers on Human Ecology, Material Culture, Area of Interest (Biocentered Design and Structural Colour), and Methodology.
- Completed Candidacy Exam and Dissertation Proposal.
- Developed a Dataset of Structural Colour cases.
- Designed and Developed a Taxonomic Rich-Prospect Browsing Interface to be used as a method of Academic Prototyping.
- Published one article in peer-reviewed journal, presented three papers at specialized conferences, did two research-related presentations at doctoral colloquia, presented portion of research at one public event, and presented four posters at related symposia.
- Conducted StrC Study, data collection, and data analysis.
- Wrote this Dissertation.

[98] The summary is not strictly chronological; some steps were developed along several stages, or interrupted and finished at later stages.

The next list summarizes the claims and concepts reviewed based on epistemological and philosophical foundations, and the area of focus of this dissertation:

- The role of designers as problem identifiers, generalists, and reflective practitioners in a field highly contextualized in wicked problems, and a civilization highly fragmented by anthropocentrism and overspecialization.
- Contrasting anthropocentrism, a biocentered standpoint places nature and life at the center of relevance and humans as a non-exclusive part of it.
- Biocentered thinking is an ethical point of view that extends inherent value to all living things, not only humans, in order to contribute to sustainable futures.
- A regenerative–biocentered design approach is conducive to sustainable innovation and the transition to long-term effective solutions.
- Materiality can be an anthropocentric construction, and nature is often seen as opposed to culture. From a posthumanist standpoint nature and culture are not opposed but rather intrinsically entangled. Material culture methodologies, if critically reflected upon and transformed, can contribute to a transition from current anthropocentric to biocentered design practices.
- Human ecology can be enhanced from a human-centered discipline to a biocentered discipline. Radical Human Ecology is a human ecologist biocentered approach that has the potential to connect human ecology and design, and biomimetic design to science.
- Biomimicry and human ecology are transforming disciplines, situated at a shifting point in the transition from a dominant paradigm. Synergies and commonalities between the two disciplines help create the conditions to evolve from an anthropocentric to a biocentered ethos.

- One of the most promising areas of biomimicry innovation is structural colour, but there is still much to learn from nature in order to benefit from it.
- The way colour is produced in products and the built environment is unsustainable. Mimicking structural colour from nature can contribute to developing new technologies and methods to produce colour sustainably and more efficiently.
- New findings on the science of structural colour are promising for design innovation, and invite researchers to build more bridges to connect science knowledge with design; the StrC can effectively contribute to connect these realms.

These claims and concepts entail the epistemological and philosophical core of this research, and convey an invitation, an opportunity, to other researchers from science, design, human ecology, and perhaps other disciplines, to expand discussions and research on the subject matters.

6.2 Limitations and Opportunities

A two-part correlated research question initiated this research project: *How can a biocentered design approach to colour help bridge gaps between scientific knowledge and biomimetic design practices? How can available scientific information/knowledge on structural colour be better organized and more accessible to bridge such gaps?*

The answer to the first part of the question—supported by evidence revealed in the findings—is that a biocentered design approach to colour makes it possible to create research tools such as the StrC, which offer a way to address existent inter and intradisciplinary gaps derived from anthropocentrism. The answer to the second part of the question is that a rich prospect browsing environment used as an academic prototyping process (such as the StrC) can make available scientific information on structural colour more accessible and better organized for designers and biomimetic innovators.

Guided by the first part of the question, the first objective of this research project was to understand the origins and reflect upon ways to bridge disciplinary gaps in the context of anthropocentric disciplinary fragmentation (Moran, 2010). Inter and intra disciplinary communication gaps can be understood as the result of “overspecialization blind alleys” (Koestler, 1967). As an extreme comparison and yet a useful metaphor, what we observe from nature in overspecialized species is stagnation and extinction. When species adapt to the conditions of the environment and/or interact and modify it for their survival, overspecialization is prevented, and new spaces of generalization—“the specialty of generalizing” (Strauss, 1990, p. 1)—can be open for developing new capabilities. A biocentered approach infers a generalist approach to solve problems, decentralized, more holistic, and systems-level oriented, inspired by the way nature works. This way of thinking stirred this research to adopt a multidimensional, multi-method approach to do research, although not without several kinds of limitations.

6.2.1 Limitations of Multiple Disciplinary Languages

“Speaking the language” of science also involves understanding its language variations or disciplinary “dialects” (e.g., biology and physics) and its “accents” (e.g., entomology and biophotonics). “Speaking the language” of design also involves using “dialects,” and “accents”; from designers’ “speaking” engineering and product design, to visual communication, interface design, and user-experience design. Communicating unambiguous meaning for a variety of inter and intra disciplinary “speakers” requires, along with a conciliatory intention, a simple yet flexible language that adapts to the needs of the different interlocutors. StrC uses all the power of visual communication and interface design languages, and the flexibility of an academic prototyping scenario to tackle such challenges. The StrC environment—the interface, the widgets, all its components and features—proposes a common language that combines visual representations with original sources of data. This primary "visually coded" language facilitates removing disciplinary biases and offers a "universal" mode of communication by using visual conventions (e.g., prioritizing a species photograph over or next to its scientific name; organizing elements and layout for an intuitive navigation, etc.). As a result, scientists and designers feel comfortable with material they may not be familiar with, and still read it with interest, as the study demonstrated.

Working with scholars from multiple disciplines and different disciplinary languages was not a minor challenge for this project; the way these kinds of limitations were handled required time or, more precisely, a period of "training" during which this researcher worked on a comprehensive literature review that included articles from a variety of disciplines. An additional measure for this "training" was to establish a permanent—although informal—dialogue with multiple scholars (in particular, scientists) from multiple disciplines asking them the same or similar questions to identify, discuss, and reflect on their different approaches, ways of knowing, and ways of communicating. This exercise anticipated and later served the design of the study.

6.2.2 Limitations and Biases of Disciplinary Knowledge

What a scientist well-informed on design matters knows about design is not measurable against what a designer well-informed on science matters knows about science, basically because both realms differ in the "ways of knowing" (e.g., one is predominantly practice-based, the other theoretical and evidence-based). The epistemologies of design are defined by the acts of the design practice. Design is "to invent, to project, to program, to coordinate a long list of human and technical factors, to translate the invisible into the visible, to communicate" (Frascara, 2004, p. 3); all these acts involve deliverable outcomes that did not entirely exist before—for example, a new product, a service, a built environment, a strategy. The epistemologies of science contrast with this definition in the way “practice” is conceived. Scientists at labs or “in the field” explore, experiment, observe, and describe what “reality” delivers, seeking the “truth,” and in this process they “forge a pathway” (Latour, 1999, p. 61) from ignorance to certainty, which implies actions such as “reduction, compression, marking, continuity, reversibility, standardization, and compatibility [of the observed reality] with text and numbers” (Latour, 1999, p. 61), often led by precedent studies and contested theories. Methodological decisions of both realms are influenced by these essentially different ways of “doing” design and science, with consequences in the disciplinary “languages” used, and disciplinary isolation side-effects that result.

Epistemological and methodological differences play an important role in isolating many disciplines this way, and this “thinking-in-silos” effect is a common limitation that biomimicry practitioners—multidisciplinarily oriented—have to deal with. There are commonalities between realms though (e.g., the *ethos* of “figuring things out” is shared by both scientists and designers; Acorn, 2019); and it may be opportunities to learn from each other (e.g., linking scientific knowledge to design practice and vice versa). The StrC study revealed signs of all these: biases, limitations, and opportunities. In some cases these limitations manifested in the form of scientists assuming (most incorrectly) what would be relevant from science to designers and broader audiences, and in other cases the limitations appeared in the form of designers assuming (most incorrectly) that something relevant for them was also relevant for scientists. In these differences there is also an opportunity to rectify wrong assumptions and clear up biases. Scientists can notice that aesthetics is not a design goal but a design result from purpose; designers can notice that science does not pursue complexity, but on the contrary it tries to simplify and make sense of things that may be complex to understand otherwise. Perhaps scientists may discover that functional aesthetics provided by design is beneficial for a scientific process (e.g., to include more visual cues to explain data), and designers may discover that science is an open invitation for multidisciplinarity, and a playground for communication.

Guided by the second part of the research question, this study investigated ways to better organize and facilitate access to scientific knowledge on structural colour with potential biomimetic design implementation, using the StrC as a research tool. Opportunities and new questions arose after collecting the findings. For the future development of the StrC as a research tool, and based on feedback collected from study participants in Chapter 5, a summary of suggestions and opportunities is listed in the next section. Overall, and according to the study participants, the StrC delivered a significant experience that made it possible to foresee the concept's long-term potential. The full development of this and other research tools like the StrC can ease or remove inter and intradisciplinary gaps between science knowledge and biomimetic design implementation. Structural colour is one subject among many that could benefit from this kind of experience.

Besides the potential and opportunities that may arise, new questions on the evolution of the StrC and on the science of structural colour are also the result of this research experience.

6.3 New Questions on the Evolution of StrC and Science of Structural Colour

6.3.1 How Can the StrC Evolve to Be a More Comprehensive Database?

The findings of the study indicate that the StrC could, in the future, grow to a more comprehensive research tool and database on structural colour. In part, this was anticipated by studying precedent databases and repositories that may feed future versions of the StrC (Chapter 4). But responses from the study also offered new ideas to guide future development and study.

For instance, the grouping features of the rich-prospect browser could advance to include a broader selection of taxonomic variables. Right now, the StrC offers selection tools based on a few variables, by basic colour hues, keywords, and a basic nomenclature of mechanisms (1D, 2D, and 3D). Including new variables of wavelength, structures, materials, and CIE mapping could result in increasing accuracy and relevance of the taxonomic results. Another aspect of the StrC is offering richer supporting imagery that may include TEM in addition to SEM. The StrC database may increase considerably with the access to external repositories (such as the list suggested in Chapter 4.2), and this expansion would make the current and future features (e.g., the widgets) fully functional, and it could also require the development of new features and tools. With such improvements, and as is suggested in the comments from participants, the StrC could set an important precedent for the advance of structural colour biomimetic implementation.

6.3.2 What Is the Material of Debate on the Science of Structural Colour?

Several aspects of the science of structural colour were identified as topics under debate or useful to discuss (Fig. 6.01). Classifying structural colour by function rather than, for instance, spectra (wavelengths) or colour hues is sure to result in a variety of opinions from scientists. There is nothing wrong with classifying by colour hues; however, it could be a simplistic measure. Classifying by function seems more relevant but also more complex; several functions can be involved and even unknown. Usually, more than one function can apply to biological functions of colours depending on the context. Establishing a function linked to a colour requires testing behaviour, visual perception, and other evolutionary factors of survival, and this adds a degree of uncertainty. Evolutionary biology even denies function as a teleology concept, which additionally complicates communication between scientists and designers, while designers clearly see the function as an applicable feature.[99] Classifying colours by wavelength may seem interesting but could be pointless too, since the interaction of several wavelengths is often observed in the same species with the same structural colour mechanisms, and can be a more complex phenomenon to measure. Categorizing structural colour through possible human applications is a less complicated option and could be useful, although not necessarily a biocentered approach to learning structural colour from nature.

The number, variations and/or combinations of structural colour mechanisms seem to be still under scientific debate, although some scientists think this is a matter of semantics and human communication rather than a scientific discussion. Agreement, or at least less ambiguous and consistent terminology to identify and classify mechanisms of structural colour, could just take time to reach. The StrC could contribute in this direction.

Convergence in evolutionary biology is another interesting and important conversation for scientists. This conversation in the arena of structural colour could be captivating (e.g., associating the same or similar colour mechanism with a similar function in different species and ecosystems). The idea behind the StrC Phylogeny widget was inspired in this terrain of inquiry. For scientists, convergences are located mainly in the hypothetical arena; it is difficult to experimentally test them, and findings may present many exceptions and unknowns. Discussions about the matter, even speculations, seem relevant for tools like the StrC.

The abundance of one colour hue over the scarcity of other, either structural or pigmentary (e.g., abundant structural blue versus scarcity of pigmentary blue in animals), is another discussion that leads to different speculations on adaptation, resources, species' strategies, and other reasons to explore the phenomenon. This was extensively examined in the

[99] This point was further discussed after the study with the scientific advisor to the StrC, Dr. Terzin.

findings chapter (Chapter 5; particularly under interview question 4). Nature teaches us many lessons about adaptation and survival, and the presence of structural hues is no exception. Blue colour, for instance, is hard to afford with the natural elements available on this planet, while other hues like reds and yellows result from pigmentary common polymers (e.g., chitin, melanin). For species to afford blue, and only if it were relevant to survival, other solutions were needed, such as evolving surfaces with structure—that is, structural colour—to produce those results. Scientists generally agree with this approach, but of course there are other aspects that make full understanding of colour more complex (perception, physiology, etc.).

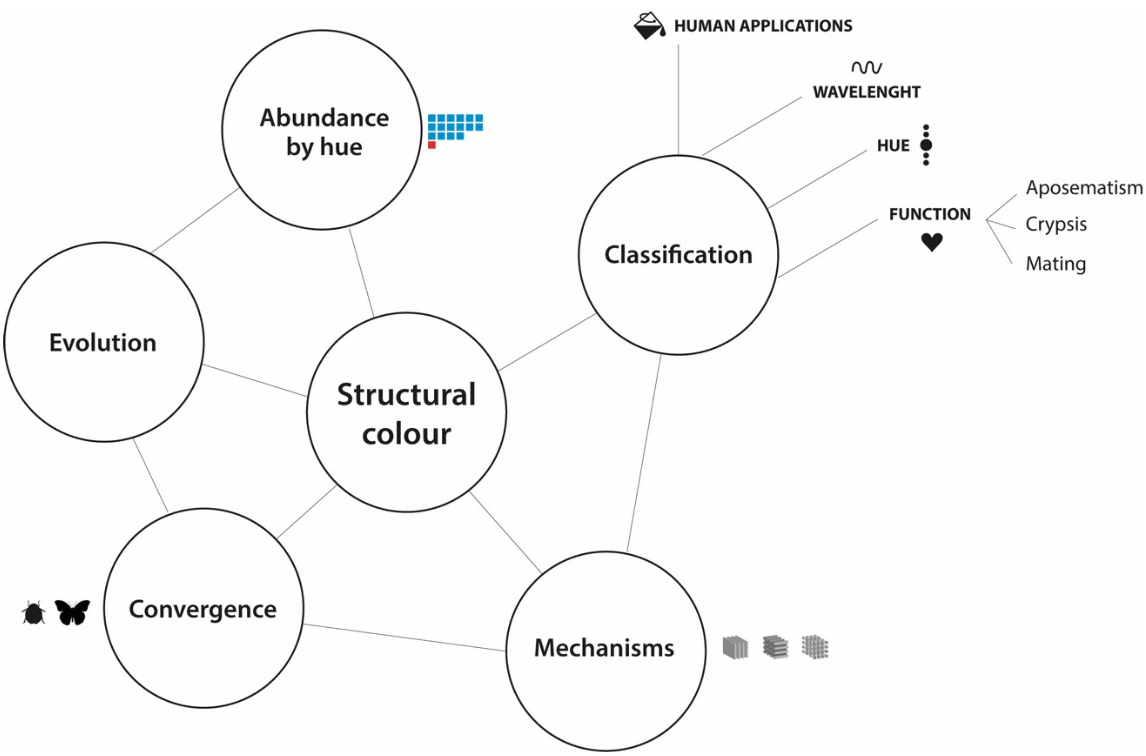

Figure 6.01. The topics of discussion identified from findings of the StrC study.

6.4 Recommendations

There are three main areas from which this research can offer recommendations to other researchers interested in biocentered design, conducting similar studies, and/or developing similar research tools:

1. Discussions on theories: Identifying, investigating, and discussing key literature in areas of anthropocentrism, sustainability, biocentrism, biophilic design, biomimetics, and human ecology to better understand philosophical and epistemological implications towards biocentered design thinking.
2. Methodological recommendations that may help to make decisions on methods and strategies to conduct studies using academic prototyping cases for research. A multidimensional approach to conduct this kind of research study is a foundational step.
3. Empirical recommendations: Developing multidisciplinary research tools like the StrC demands good planning and flexible goals encompassing the academic-prototyping process that generates operational versions of the tool. A series of necessary steps to develop the StrC for the long term may also be useful for other similar developments, other rich-prospect browsing interfaces, other precedent databases, and the design of other cross-collaborative interfaces.

6.4.1 Discussions on Theories: Towards Biocentered Design Thinking

As was argued in the literature review chapter (Chapter 2), a biocentered approach may inspire new means of creation, fabrication, production, and distribution aligned with a circular economy, while encompassing the transition from an anthropocentric to a regenerative and ultimately sustainable stage (Wahl, 2016). Emergent design disciplines such as biomimicry can be aligned under this transition and with the idea of radical human ecology (McIntosh, 2012), which proposes to interconnect disciplines under a more holistic view and common goals, in this case human ecology and design, and design to science.

Design is an integrative discipline (Buchanan, 1992). It is imperative to expand human-centered approaches to life-centered approaches in the minds of designers. It is recommended to move from a material culture structuralist standpoint, which considers nature as opposed to culture, to an integrative, biocentered culture, and posthumanist standpoint, which considers nature and culture not opposed but intrinsically entangled (Bennett, 2010).

6.4.2 Methodology: Multidimensional Approach and Academic Prototyping Method for Research

A multidimensional epistemological approach shaped the methodological orientation of this research, and made it possible to determine the multiple methods applied. The combination of these methods to conduct the StrC study gave rich results for analysis, and good lessons were learned. Among these methods, the academic prototyping experience combined with a rich-prospect browsing interface used as a digital probe opened a new terrain for exploration in the realm of dynamics tools for interdisciplinary research. This synergetic combination of methods merits further exploration and implementation.

Among the lessons learned during the study, the following points may help future researchers to apply and improve the methods and strategies used in the StrC independently of the subject matter:

- Multidisciplinary research demands additional time, and additional recruitment and administration measures. The StrC study needed participants from different disciplinary realms (i.e., science, design) and also, given the dissemination of the subject matter (biophotonics), from different parts of the world, to engage remotely (to a survey and email exchanges). It is recommended to start planning the research as early as possible, anticipating possible limitations, identifying possible target groups (professional associations, networks, and social media groups related to the subjects), and assigning time for the preparation of all the materials needed for the enrollment (i.e., ads, texts, follow-up tools). In addition, a prolonged and flexible time frame (8 weeks or longer) is recommended to reach the target participants and adjust the timeline if necessary. Administrating this process demands tracking tools (e.g., spreadsheets, checklists) to follow up on the status of participants (e.g., tracking the number of times and frequency with which invitations were sent; counting responses to invitations; collecting consent forms, surveys, and interview responses).

- The StrC study got enough participants for data analysis after a period of 8 weeks, but if a longer time frame is possible it would be beneficial for the academic prototyping process; for instance, if the StrC continues as a long-term project, more data to improve a beta version of the tool could be collected for a period of 6 months to 1 year while the StrC is fully developed. It is recommended, however, to reduce the number of questions/points for testing, to reduce the amount of data. Analyzing a small sample for the StrC (19 survey participants, four interview participants) was time-consuming for the planned time frame of this dissertation, especially the qualitative data analysis.
- For academic prototyping studies such as the StrC, it is essential to have permanent technical support (i.e., computing science developers, interface designers) to ensure that the tool remains operational during the study, to detect and fix any glitches, modify functions if required, and modify design and programming features based on received feedback according to the proposed time frame. This also requires prioritizing:

determining what can and must be done immediately and what can wait for future development.

Overall, the aspects for improvement mentioned above did not conflict with any of the methods and strategies chosen for the StrC study, and these lessons learned suggest only minor adjustments for future, similar planning. Nevertheless, researchers must be aware of possible complications if these methods and strategies are combined with other methods not included in this research project. A multidimensional methodological approach is a conceptual direction, and does not comprise a formula *per se.*

6.4.3 Empirical Recommendations: Future Steps of StrC Development

The findings suggest that the StrC has potential, and therefore future development will be necessary. This understanding is supported by scientists, designers, and biomimicry practitioners alike. In order to continue developing the StrC as a long-term project or to inspire other projects such as the StrC, a number of essential recommendations, steps, and actions must be considered. The following list summarizes these recommendations:

- User Experience (UX) evaluations in combination with further academic prototyping process and studies.
- Automation of data collection from external repositories, data cross-verification, and validation system for external entries.
- More interaction and control for users in the red layer contributions mechanism.
- Automation of contributions and communication space for networking (scientist-designer-scientist), forum, chatroom, and/or integration with third-party applications (Slack, Google, etc.).

- New section on applied and under-development materials and products, based on available peer-reviewed literature on the subject matter.
- Enhancement of the colour-picker function (e.g., a slider) to include the wavelength range, combined with mechanism options.
- Inclusion of a CIE map to compare observed hues in the visible spectrum to industry colour conversions (such as RGB, CMYK, etc.).
- Inclusion of TEM and additional spectral imagery to the widgets.
- Addition of consistent scale bars for SEM and TEM imagery.
- Completion and enhancement of the Homology (i.e., "Divergences") and Phylogeny widgets; solution of the compatibility issues between 7Vortex and the Research Map.
- Full development of Geography and Ecosystem maps for species, based on available metadata and Google Maps tools.
- Reevaluation and reconsideration of Evolutive Disruptions widget.

Other research tool projects that may consider a rich-prospect browsing interface as a good choice may find the StrC features useful, even for collecting different kinds of data—for example, other taxonomic collections from art museums, material culture artifacts, product or industry catalogues. The hermeneutic visualizations for data manipulation and customization, combined with mapping, search, and accessing literature tools, makes the StrC a precedent case for other similar design developments.

6.5 Final Remarks

Human civilization faces tremendous challenges to change the effects of anthropocentrism, and survive and thrive in a sustainable future. Designers and scientists are central actors in facilitating the necessary transformations to first regenerate our ways of knowing and doing into an integrative process that includes nature at the core of methodologies, and then to sustain such integration for the long term. Contemporary disciplines still oscillate between anthropocentric and biocentered thinking, and the challenge is to pave a paradigmatic transition to expand a narrowed view into a more holistic one that removes disciplinary boundaries, as was remarked in the initial chapters of this dissertation. The transformation that biocentered thinking proposes requires fluid disciplinary exchanges, mutualism, and cooperation. Challenges that come with these requirements deal with disciplinary egos, and may imply political and even ideological biases. These challenges are associated with moving from an anthropocentric position that isolates individuals—an eccentric behaviour by the standards of nature—to a biocentered position, one that follows what nature can teach us, integrates individuals and disciplines under the same dialogic level, and makes them interdependent as in healthy natural ecosystems.

Exploring different disciplinary realms, discovering connections and opportunities, and sparking innovation was part of the proposed academic prototyping experiment with the StrC. Designers, human ecologists, and biomimicry practitioners may find this reflective practice useful to explore, discover, and innovate, guided by a biocentered human-ecologist way of knowing and doing. Scientists may find the tools and methods proposed in this research relevant to disseminate scientific knowledge, make it more accessible, and open space and dialogue for biocentered applications. The StrC experience serves as a space to open such dialogues and bridge existing disciplinary limitations. As stated in the introduction to this dissertation, researchers from different disciplines (other than biomimetic design and the science of structural colour) who are interested in biocentered thinking, biomimetic sustainable innovation, and interdisciplinary research tools may find opportunities to enrich their own research in the epistemological, methodological, and empiric work done in this dissertation.

The continuation, directly or indirectly, of the StrC as a tool kit for interdisciplinary research, and as a space to connect scientific knowledge to biomimetic design innovation, is an asset of this dissertation. Before and after conducting the StrC study, and while this dissertation was being finished and polished, a number of scientists and designers manifested interest in getting involved in future collaboration projects linked to the StrC. Academics already familiar with this project find the StrC an innovative method to practice research in collaborative projects, in courses from multiple disciplines (e.g., product design, biology, material engineering, computing sciences), in class activities, and assignments. It is my intention beyond this doctoral work to keep those links active, and keep developing and adapting the StrC to be implemented in multiple situations and environments.

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Appendices

7.1. Deliverables of the Study

7.1.1 Ethics Approval Documents

RESEARCH ETHICS OFFICE

308 Campus Tower
Edmonton, AB, Canada T6G 1K8
Tel: 780.492.0459
Fax: 780.492.9429
www.reo.ualberta.ca

Notification of Approval

Date:	November 27, 2018	
Study ID:	Pro00085144	
Principal Investigator:	Carlos Fiorentino	
Study Supervisor:	Megan Strickfaden	
Study Title:	StrC - Rich Prospect Taxonomy on Structural Colour: A Tool for Research to Connect Nature's Scientific Knowledge and Biomimetic Design Innovation	
Approval Expiry Date:	Tuesday, November 26, 2019	
Approved Consent Form:	Approval Date 11/27/2018 11/27/2018	Approved Document Consent form Information Sheet (print)

Thank you for submitting the above study to the Research Ethics Board 2. Your application has received a delegated review and has been approved on behalf of the committee.

A renewal report must be submitted next year prior to the expiry of this approval if your study still requires ethics approval. If you do not renew on or before the renewal expiry date, you will have to re-submit an ethics application.

Approval by the Research Ethics Board does not encompass authorization to access the staff, students, facilities or resources of local institutions for the purposes of the research.

Sincerely,

Ubaka Ogbogu, LLB, BL, LLM, SJD
Chair, Research Ethics Board 2

Note: This correspondence includes an electronic signature (validation and approval via an online system).

Acknowledgement Form

Date:	March 22, 2019
Study ID:	Pro00085144
Study Title:	StrC - Rich Prospect Taxonomy on Structural Colour: A Tool for Research to Connect Nature's Scientific Knowledge and Biomimetic Design Innovation
Principal Investigator:	Carlos Fiorentino

Thank you for your submission of Email Interviews consent, Information letter for interviews & Email Interview to the Research Ethics Board 2. We acknowledge receipt of these documents which will now form part of the approved documentation for this study.

Sincerely,

Anne Walley
REB Specialist, Research Ethics Board 2

Note: This correspondence includes an electronic signature (validation and approval via an online system).

7.1.2 Study Protocol

StrC: A Tool for Research to Connect Nature and Design

Study Protocol

Preliminary guidelines for participants

Prior to the beginning of the study, participants will receive a brief guidelines document by email, with the purpose of helping them to quickly find and test the StrC.online interface. This preliminary guideline will ask participants to open any browser in their computers to participate of the study navigating the StrC site.

Project Information and Consent

When participants access StrC.online a home screen with a brief introduction of the research team and the project, and how to read the information sheet and fill the consent form will be prompt. A link to contact the principal investigator will be available to answer any questions posed by the participants at all times. After reading this first screen, participants will be asked to click on a "Continue to information document" button. The next screen will show the information sheet with all the details of the research project, with the option to download the document for participant's records. After reading this second screen, participants will be asked to click on a "Continue to consent form" button. Participants will be asked to read the consent screen and click the "Accept" button if they decide to continuing participating in the study. Accepted forms will activate a notification via email that will be collected by the principal investigator.

Introduction and guiding instructions

After participants accept to continue, a new screen with a list of points to find, explore and investigate features of StrC will be shown, with the intention to execute certain tasks with the underlying idea of comparing similar activities along the sample for data analysis. An option to download/print this list as a document for participant's records will be included in the screen. At the bottom of the screen a "Continue to StrC interface" button can be clicked.

Exploring the StrC interface

When participant click on the "Continue to StrC interface" button, it will prompt a new window with the home page of StrC interface. The Guiding instructions will remain open in the previous window. Participants will follow the guidelines and/or freely explore the interface with no time limitation. The backend of the StrC system will collect and record the activity of the website, looking for patterns and key elements that reveal the effectiveness of the interface features (without affecting participant's activity). No personal information will be collected at any time.

Sending feedback through an online survey

When participants finish the exploration, they will be asked fill the survey accessible from the home page. When the StrC window is closed without accessing the survey, an invitation to fill the survey will be automatically sent by email. If participants leave the interface open, after 24 hours of inactivity the system will automatically send this invitation too.

The message in the email with thank the participant for exploring the StrC tool, and will invite to fill an online survey. A link in the message will provide access to the survey. Email addressed will be already associated with the participant from responding to the link sent after participating in the StrC exploration.

Once the participants access the survey site, a first home screen identified with the StrC project, contact information of the research team, and a reminder on confidentiality and generalities of the study (also included in the original information sheet) will be prompted. By clicking a “Continue to the survey” button participant will access the first page of the survey.

The first page of the survey will ask for basic demographic information:

(a) Discipline / Professional Area

(b) Institution affiliation

(c) Level of education and training (degrees, diplomas and certifications)

Depending on the choice on option (a), participants will be redirect to either the “designers” or “scientists” questionnaires.

Both are self-administered questionnaires that follow a consistent template to allow and collect responses seamlessly. They include about 10-12 key questions to determine the effectiveness of their experience exploring StrC, and include text fillable boxes for collecting additional comments. The questions will be in form of statements followed by a five-point scale "ranking": strongly agree, agree, neutral, disagree, and strongly disagree. Once the survey is complete, the last page will thank and ask participants to click on a “Submit” button.

Closure

Once the survey is submitted, a final message will be prompt thanking for contributing to the study and inviting participants to keep contact with the research team and the StrC project for future opportunities of collaboration, or the possibility of scheduling an interview for additional feedback.

Potential interviews (optional post-exploration and survey)

If the possibility of additional feedback –in particular from scientist participants– is identified from comments and responses to the survey, a few participants may be contacted to schedule an interview for additional contributions. This could be done simply by exchanging emails or by contacting them via Skype. Alternatively, face-to-face meetings could be arranged depending on travelling feasibility. A semi-structured interview guide based on the topics to be discussed would be developed for such purpose.

7.1.3 Consent Forms and Disclaimer About Collecting Personal Information

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StrC: A Tool for Research to Connect Nature and Design

Consent Form (print version)

Principal Investigator:

Carlos Fiorentino, PhD Candidate carlosf@ualberta.ca 1 780 707 7541

Department of Human Ecology 302 Human Ecology Building,

University of Alberta, Edmonton, T6G 2N1

Do you understand that you have been asked to be in a research study? ☐ Yes ☐No

Have you read and received a copy of the attached Information Sheet? ☐ Yes ☐ No

Do you understand the benefits and risks involved in taking part in this study? ☐ Yes ☐ No

Have you had an opportunity to contact the researcher to ask questions

and discuss this study? ☐ Yes ☐ No

Do you understand that your participation is voluntary? ☐ Yes ☐ No

Has the issue of confidentiality been explained to you? ☐ Yes ☐ No

Do you understand who will have access to your information? ☐ Yes ☐ No

Are you willing to be contacted for an interview in the future? ☐ Yes ☐ No

☐ I am 18+ years old

By checking this box you agree to participate in this study:

☐ I agree to take part in this study

If you have any questions about your rights as a participant, please contact the University of Alberta Research Ethics Board at 1.780.492.2615 Re: Pro#00085144

7.1.4 Information Sheet for Participants With the Description of the Study

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StrC: A Tool for Research to Connect Nature and Design

Information Sheet (print version)

Principal Investigator:

Carlos Fiorentino, PhD Candidate carlosf@ualberta.ca 1 780 707 7541

Department of Human Ecology 302 Human Ecology Building,

University of Alberta, Edmonton, T6G 2N1

Project Summary

Biomimicry (also known as biomimetics) is an emerging multidisciplinary field that offers successful and time-tested models of design for sustainability. Biomimicry draws on "nature's best ideas" and then emulates them to address societal problems by design, for example, mimicking the way nature produces colour without using toxic chemicals and wasteful processes. Advances in new materials for structural colour production could be game-changers for print and colour applications; for the screens of phones and other devices; and for signaling and communication strategies, to name a few. While many designers yearn to innovate with structural colour, finding, understanding, and implementing scientific information into the design process is a major challenge. Physicists, biologists, and designers often live in disciplinary silos that holdup progress on this front.

The goal of this project is addressing this problem from an angle of facilitation and mediation, through an ecosystem of research digital tools that facilitate access to available scientific knowledge. It intends to fill communication gaps between scientists and designers involved in current biomimetic projects, as well as inspire new ones. This study consists of testing such tools, which main interface resembles a website.

How is this research project being done?

We are inviting designers and scientists from the international community interested in applying structural colour for biomimetic innovation to participate in this study. Participants are provided with access to the StrC interface available on line and asked to explore the complete digital environment, with a set of guiding questions/cues to test the potential use as a tool for research beyond a prototype stage. The tool will be able to collect data from such activities, and it will allow the researchers to identify patterns, commonalities, differences, and other important cues to reflect on future development of the tool. Participants will be also asked to provide feedback through a brief online survey, aimed to find evidence to support or challenge the main hypothesis of the study.

Participation

If you are reading this information sheet, the principal investigator has contacted you as a potential participant in our research and gave you access to the StrC.online interface. After finishing exploring the StrC interface you will be asked to fill an online survey to provide feedback. Your participation in these two instances is completely voluntary and you can withdraw at any time from any part of this process, by just interrupting your activity online. Withdrawing will not prevent you from participating again in the study at a later time. Your full participation will include:

1- Exploring the Strc.online interface. We estimate that you will need a minimum of 20 minutes to follow the guiding instructions, however you can use it for as long as you wish up to 2 weeks, and as long as you do not exceed 24 hours of inactivity (in which case the session will be automatically interrupted). There is no need of sign-up / sign-in to the system, your personal identifiable information is not needed for this study.

2- Filling an online survey with 10-12 questions related to the subject of the study and connected to your area of expertise (design or science). This questionnaire will collect your feedback about the experience using the StrC.online interface.

Benefits and Risks

Exploring the StrC.online interface will provide clues on how to improve connecting scientific information —on structural colour in nature— to design innovation—biomimetics of colour. The study may reveal opportunities and unseen characteristics from both realms (science and design), and it may confirm or challenge previous assumptions and hypotheses, while creating synergies for cross-collaboration. The post-experience survey is aimed to collect comments, suggestions and critiques for potential improvements of the project.

This study will benefit scholarship on this topic, as well as provide information to support future development of the tools proposed. The ultimate intention of this project is to improve communication between scientists and designers involved in current biomimetic projects, as well as inspire new projects on structural colour.

There may be no direct benefits to participants. However, it may be indirect benefits to designers and scientists participating of the study, such as accessing information that may benefit their own research and projects, as well as interest in participate in future stages of the StrC environment.

There is no risk to you and others in participating in this study, other than spending some extra time if you need to deeper explore the tool.

Compensation

There is no material compensation offered for participating in this study.

Confidentiality

This research focuses on the interactions of participants with the StrC interface and the outcomes of such interactions. No identifying data, such as your name, will be collected, either from your activity with the interface or the survey. Your comments and responses will be kept anonymous, and will not be associated with email or IP addresses; the data collected from the interface and the survey will be coded to ensure anonymity. You can withdraw either from using the interface or the survey at any time, by just interrupting your activity online (closing the windows in your browser). Personal data provided in consent will not be associated with a particular participant.

The researchers will keep the raw data collected from interface activity and survey indefinitely. Only the StrC research team will have access to the collected information. All efforts under the guidance of the University of Alberta are made to protect your information.

Questions or concerns

If you have any further questions about this project, please contact Carlos Fiorentino: carlosf@ualberta.ca 1.780.707.7541, or Dr. Megan Strickfaden: megan'strickfaden@ualberta.ca 1.780.492.3012.

If you have any questions about your rights as a participant, please contact the University of Alberta Research Ethics Board at 1.780.492.2615 Re: Pro#00085144

Thank you so much for your participation and support.

Sincerely,

Carlos Fiorentino, PhD Candidate, Human Ecology

7.1.5 Step-by-Step Guidelines Document

StrC: A Tool for Research to Connect Nature and Design

Guiding Instructions for Exploring the StrC.online Interface

Dear participant, these guiding instructions will help you to quickly access and explore the StrC.online interface, and will suggest different ways to find the main features of the research tool. Please follow the steps below and enjoy the experience!

Setting Up

We recommend using a personal computer (desktop or laptop) to participate in this study, tablets and smartphone may not function properly to either see the full features of the interface or the survey. A reliable internet connection will be necessary. StrC interface and posterior survey can be opened in any browser and platform. If you find any technical issue please contact the principal investigator: carlosf@ualberta.ca

Step 1:

Click on the link below

strc.online/study

Your default browser application in your computer will open automatically showing a welcome screen to the StrC website. If this is not the case, you may need to open your browser manually and copy and paste the link into the browser's address header. The welcome screen displays a brief introduction of the research team and the project. Before you are set to start navigating the StrC interface a few formal steps will be first required to continue.

Step 2:

Enter your email address, click "Next" and another screen with an information sheet will be displayed. Please read carefully the points described. This sheet can also be downloaded / printed for your records. A link to contact the principal investigator will be available to answer any questions posed by the participants at all times.

Step 3:

After you read click on "Next" again, and a consent form will be prompted. Please check the boxes and click on "I accept" if you wish to continuing participating in the study. Your acceptance will be automatically notified to the principal investigator.

Step 4:

After you accept to continue, a new guidelines screen with a list of points to find, explore and investigate features of StrC will be shown. Download or print this list for your records. Click on “Submit” at the bottom of the screen. A new window will be open with access to the StrC interface.

Step 5:

The new window will display the home page of StrC interface. Follow the list of suggested points from the guidelines and/or freely explore the interface with no time limitation (up to 24 hours for session). Following the points of the list from the guidelines can take 20 minutes or more. You can leave the windows opened or come back at any time to continue within the 24 hours of a session, and keep visiting and exploring StrC until the end of the study (April, 2019).

> **Disclaimer:** The StrC database contains an initial dataset with a limited number of entries (species), collected from Laboratory of Entomology at Augustana Campus, University of Alberta, and from examples available in free access repositories,[1] with the only purpose of simulating the environment of the tool for this study. The data associated to every entry has been partially curated by students from Biological Studies at Augustana Campus, University of Alberta, however you may find entire sections of StrC and many cases where information is not available or not yet curated. For the future implementation of StrC beyond this study, a comprehensive and rigorous dataset based on reliable scientific repositories, and curated by the scientists contributing to the StrC project, will replace most of the current content of this testing version.

Step 6:

When you finish your exploration please return to the StrC home page by clicking the StrC logo at the upper left corner of the screen. In the home page click on “StrC Survey” button located in the upper right corner of the screen.

Step 7:

After clicking on “StrC Survey” you can access the survey with a 10-12 questionnaire. **Completing this survey is of vital importance to collect information for the study.** We recommend to complete the survey as soon as you finish your StrC exploration, however you can spend as much time as you wish exploring StrC during the time of the study.

[1] Free access repositories such as AskNature.org, inaturalist.org, Tree of Life (tolweb.org/tree/) or Wikipedia.

7.1.6 StrC Study Access Pages and Guiding Points Page

StrC Study Access

* Required

Email address *

Your email

Welcome to StrC.online

The study. The StrC interface is a tool for research that intends to fill communication gaps between scientists and designers interested in biomimetic applications of colour. This study consists of testing StrC. We estimate that you will need a minimum of 20 minutes to navigate StrC following the guiding instructions, however you can also freely navigate StrC for as long as you wish up to 2 weeks.

The research team. The StrC study is conducted by:

Principal Investigator and Administrator:
Carlos Fiorentino, PhD Candidate Human Ecology
carlosf@ualberta.ca 1.780.707.7541
302 Human Ecology Building,
University of Alberta, Edmonton, T6G 2N1

Supervisor:
Megan Strickfaden, Professor Human Ecology
megan.strickfaden@ualberta.ca
302 Human Ecology Building,
University of Alberta, Edmonton, T6G 2N1

Before you are set to start navigating the StrC interface a few formal steps are first required to continue. Please click "Next" to go to the next step.

StrC A Tool for Research to Connect Nature and Design

NEXT

Page 1 of 4

StrC Study Access

* Required

Consent Form

Please fill the check boxes and click on "I Agree" if you wish to continuing participating in the study. Your acceptance will be automatically notified to the principal investigator.

Principal Investigator Carlos Fiorentino
carlosf@ualberta.ca 1.780.707.7541
Department of Human Ecology
302 Human Ecology Building,
University of Alberta, Edmonton, T6G 2N1

Do you understand that you have been asked to be in a research study? *

- ○ Yes
- ○ No

Have you read and received a copy of the Information Sheet? *

- ○ Yes
- ○ No

Do you understand the benefits and risks involved in taking part in this study? *

- ○ Yes
- ○ No

Have you had an opportunity to contact the researcher to ask questions and discuss this study? *

- ○ Yes
- ○ No

Do you understand that your participation is voluntary? *

- ○ Yes
- ○ No

Has the issue of confidentiality been explained to you? *

- ○ Yes
- ○ No

Do you understand who will have access to your information? *

- ○ Yes
- ○ No

Are you willing to be contacted for an interview in the future? *

- ○ Yes
- ○ No

- ☐ I am 18+ years old

By checking this box you agree to participate in this study: *

- ☐ I agree

BACK NEXT Page 3 of 4

StrC Study Access

Please read the following guiding points

PRINT OR SAVE THIS PAGE FOR YOUR REFERENCE, THEN CLICK ON SUBMIT TO ACCESS THE STRC INTERFACE

Guiding Points

StrC

The following list is intended to assist you to explore, discover and investigate features of StrC. You can follow this points in order and/or freeley navigate StrC too. You can go back to the home page from any point by clicking the StrC header logo. When you click on "Submit" a separate window will open to the StrC.online webpage. Please print or save this page for your reference while navigating StrC.

Disclaimer: The StrC database contains an initial dataset with a limited number of entries (species), collected from Laboratory of Entomology at Augustana Campus and the Strickland Museum collection at the University of Alberta, and from examples available in free access repositories,[1] with the only purpose of simulating the environment of the tool for this study. The data associated to every entry has been partially curated by students from Faculty of Science at Augustana Campus, University of Alberta, however you may find entire sections of StrC and many cases where information is not available or not yet curated. For the future implementation of StrC beyond this study, a comprehensive and rigorous dataset based on reliable scientific repositories, and curated by the scientists contributing to the StrC project, will replace most of the current content of this testing version.

1) Free access repositories such as AskNature.org, Inaturalist.org, Tree of Life (tolweb.org/tree/) or Wikipedia.

TASK 1 Click a color from the color picker and choose one available species from the collection.

TASK 2 Once you find a species profile page with available information, get familiar with the legends at the bottom of the profile page, and find them applied. You can also zoom in to details by clicking the magnifying lens icon on the photograph of the species chosen.

TASK 3 If available, identify literature related to that species.

TASK 4 Find the "Dogbane Beetle": from the homepage click on "animals' kingdom, then "invertebrates", "arthropods" class, "coleoptera" order, Chrysomelidae" family, and "Chrysochus auratus" species.

TASK 5 Get familiar with the widgets "Phylogeny", "Homology", "Evolutive Disruptions" , and "Research Map." You can click on the "Research Map" preview to access the 7Vortex visualization demo.

TASK 6 Explore the "Phylogeny" widget. Use the color picker to compare evolutionary branches within the same order with different colors. Switch orders under the same color to compare different species by clicking on the branches.

TASK 7 Explore the "Homology"widget. Use the color picker to swith colors within the same order. Select a different color mechanism from the picker to compare different orders under the same color. Click on the revealed order in the "word-ring" visuazation and observe the new data revealed on the left side of the widget.

TASK 8 Go back to (any) species profile page, then click on EDIT/CONTRIBUTE to access the "Red Layer" function. Click on a "+" square and leave a comment, suggestion or amendment. You can also upload a small file or image (1Mb or less) and/or add a link to a webpage. Don't forget to click on "SUBMIT" then "EXIT."

TASK 9 From the homepage click on the search box and type a keyword such as a color, a common name, or a scientific name of a species. Repeat Tasks 2, 3 and 8.

TASK 10 Keep exploring the taxonomy freely, combining any of the tasks for as long as you wish.

TASK 11 After finishing your exploration, go to the home page upper right corner and click on "StrC Survey" to provide feedback to the study

Print / save this page for your reference, and submit to access StrC

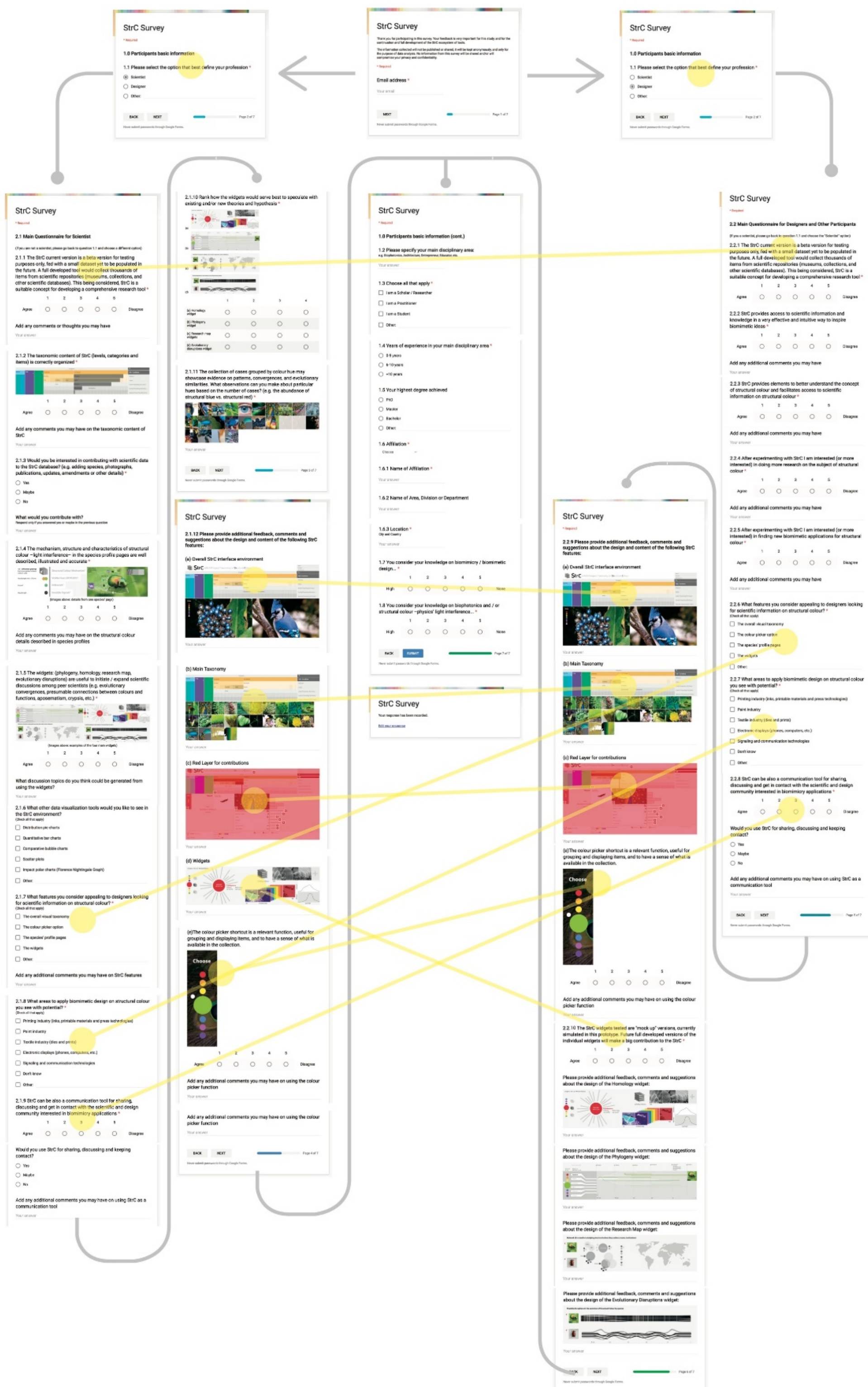
Send me a copy of my responses.

BACK SUBMIT Page 4 of 4

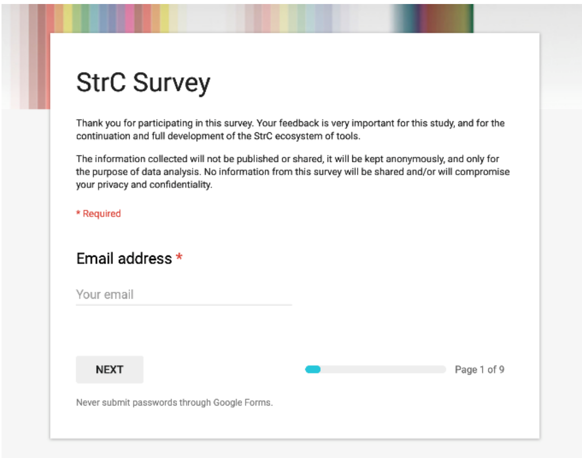
StrC Study Access

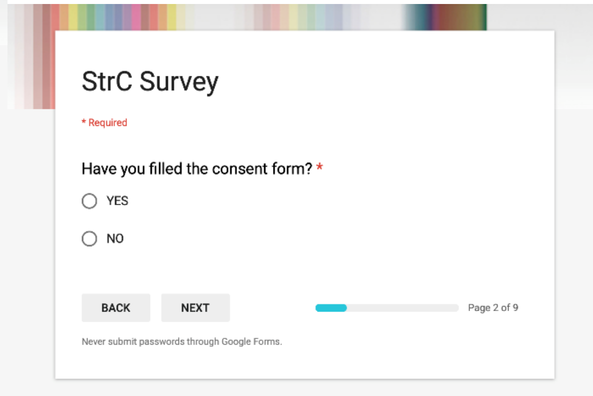
Thank you for participating in the study. Please open https://strc.online in your browser, and follow the guiding points. Don't forget to click on "StrC Survey" to give feedback when you finish the experience.

7.1.7 StrC Survey Access Page and Questionnaire

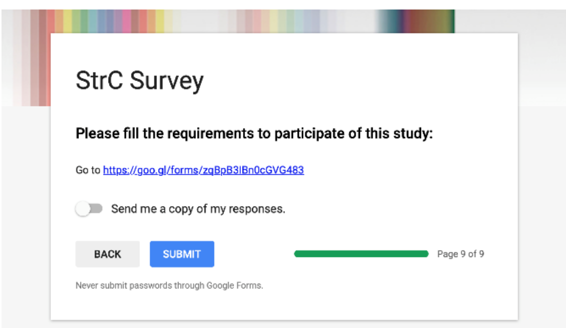


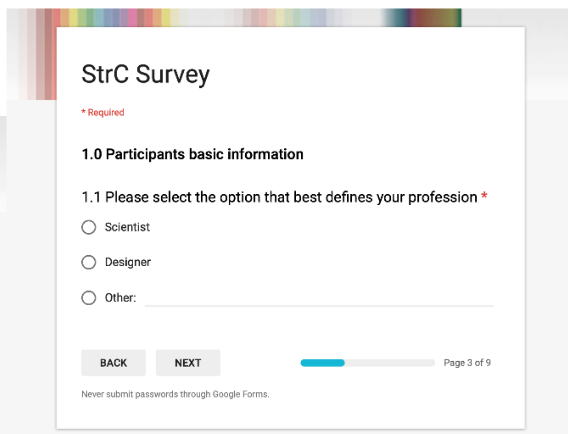
Sequence of survey sections for Scientists and Designers+ and correlation of questions between both sections.



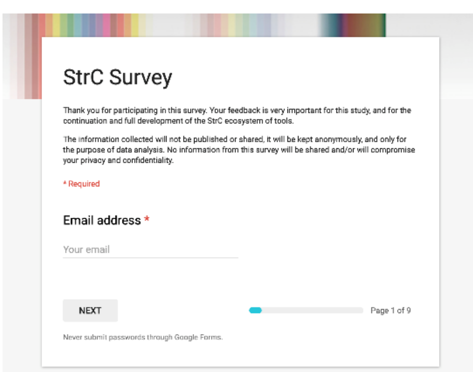


When participants click on 'NO', they are redirected to the study access pages and consent form (a); when participants click 'YES' they can access the survey (b).

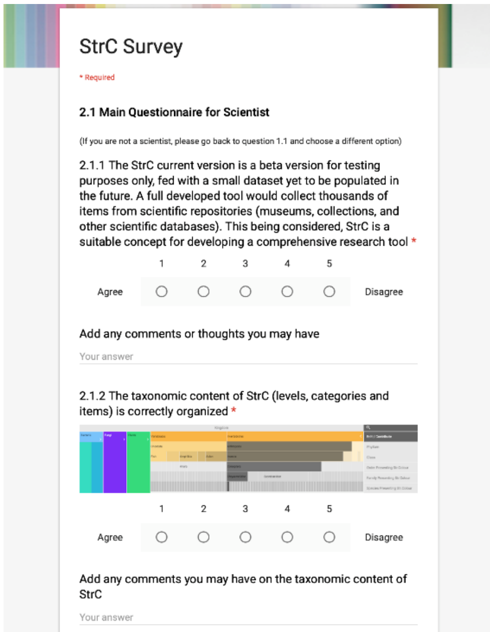




(a) (b)



Depending on the option chosen, participants are redirected to section 2.1 (Scientists) or section 2.2 (Designers and other participants).



StrC Survey

* Required

2.1 Main Questionnaire for Scientist

(If you are not a scientist, please go back to question 1.1 and choose a different option)

2.1.1 The StrC current version is a beta version for testing purposes only, fed with a small dataset yet to be populated in the future. A full developed tool would collect thousands of items from scientific repositories (museums, collections, and other scientific databases). This being considered, StrC is a suitable concept for developing a comprehensive research tool *

Agree 1 2 3 4 5 Disagree

Add any comments or thoughts you may have

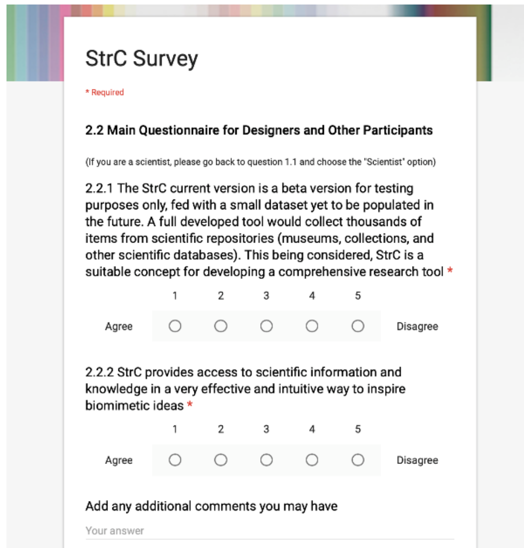
Your answer

2.1.2 The taxonomic content of StrC (levels, categories and items) is correctly organized *

Agree 1 2 3 4 5 Disagree

Add any comments you may have on the taxonomic content of StrC

Your answer



StrC Survey

* Required

2.2 Main Questionnaire for Designers and Other Participants

(If you are a scientist, please go back to question 1.1 and choose the "Scientist" option)

2.2.1 The StrC current version is a beta version for testing purposes only, fed with a small dataset yet to be populated in the future. A full developed tool would collect thousands of items from scientific repositories (museums, collections, and other scientific databases). This being considered, StrC is a suitable concept for developing a comprehensive research tool *

Agree 1 2 3 4 5 Disagree

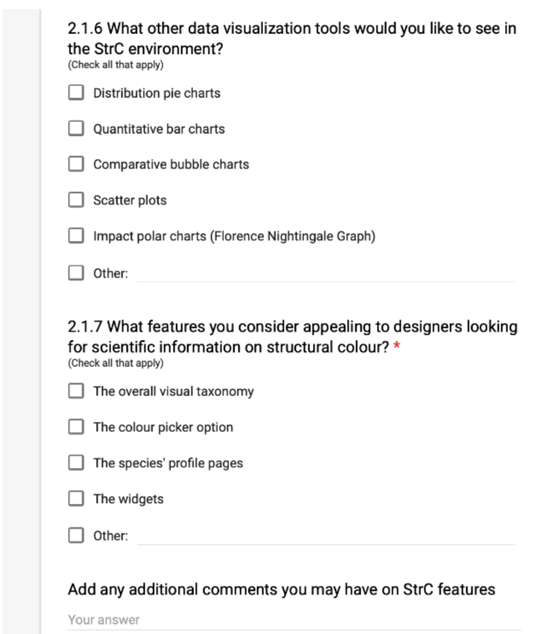
2.2.2 StrC provides access to scientific information and knowledge in a very effective and intuitive way to inspire biomimetic ideas *

Agree 1 2 3 4 5 Disagree

Add any additional comments you may have

Your answer

Many points of the questionnaire were packaged questions containing scale type, and open-ended questions.



2.1.6 What other data visualization tools would you like to see in the StrC environment?
(Check all that apply)

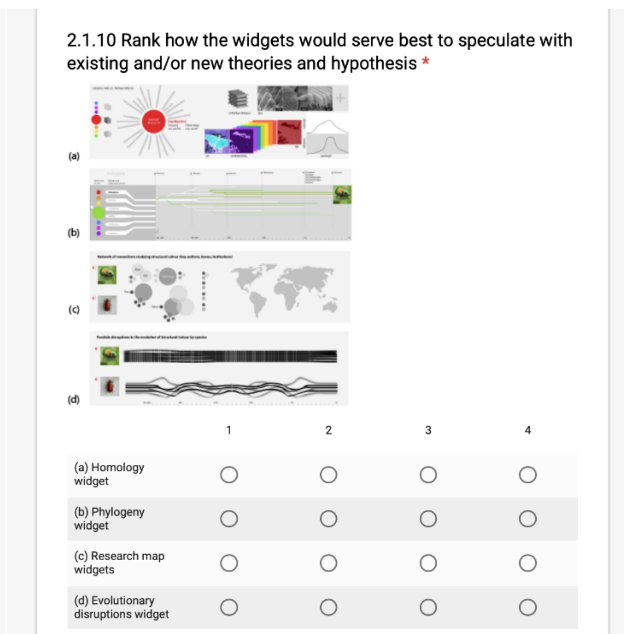
- Distribution pie charts
- Quantitative bar charts
- Comparative bubble charts
- Scatter plots
- Impact polar charts (Florence Nightingale Graph)
- Other:

2.1.7 What features you consider appealing to designers looking for scientific information on structural colour? *
(Check all that apply)

- The overall visual taxonomy
- The colour picker option
- The species' profile pages
- The widgets
- Other:

Add any additional comments you may have on StrC features

Your answer



2.1.10 Rank how the widgets would serve best to speculate with existing and/or new theories and hypothesis *

(a)

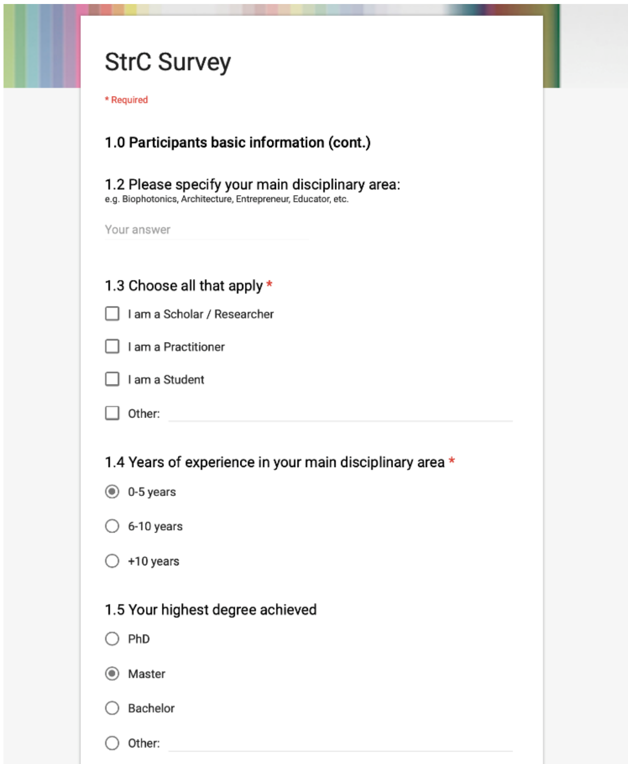
(b)

(c)

(d)

	1	2	3	4
(a) Homology widget				
(b) Phylogeny widget				
(c) Research map widgets				
(d) Evolutionary disruptions widget				

Other packaged questions combined multiple-choice, open-ended and ranking options.



StrC Survey

* Required

1.0 Participants basic information (cont.)

1.2 Please specify your main disciplinary area:
e.g. Biophotonics, Architecture, Entrepreneur, Educator, etc.

Your answer

1.3 Choose all that apply *

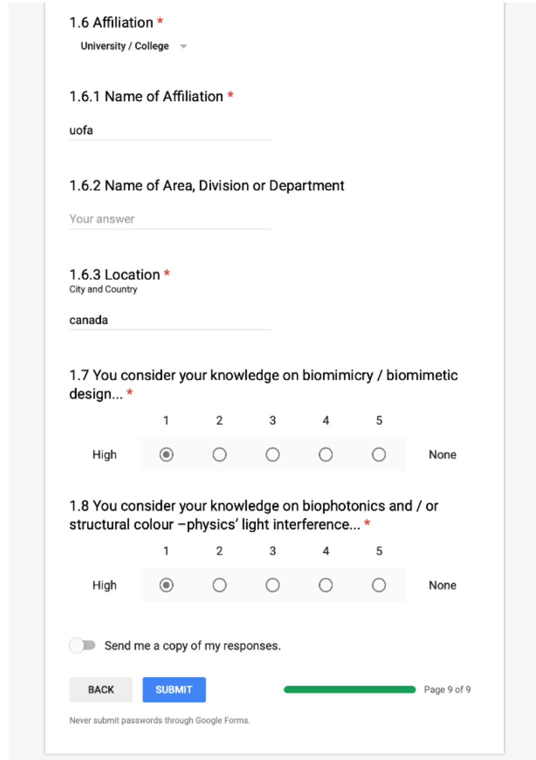
☐ I am a Scholar / Researcher
☐ I am a Practitioner
☐ I am a Student
☐ Other:

1.4 Years of experience in your main disciplinary area *

◉ 0-5 years
○ 6-10 years
○ +10 years

1.5 Your highest degree achieved

○ PhD
◉ Master
○ Bachelor
○ Other:



1.6 Affiliation *
University / College

1.6.1 Name of Affiliation *
uofa

1.6.2 Name of Area, Division or Department
Your answer

1.6.3 Location *
City and Country
canada

1.7 You consider your knowledge on biomimicry / biomimetic design... *

	1	2	3	4	5	
High	◉	○	○	○	○	None

1.8 You consider your knowledge on biophotonics and / or structural colour –physics' light interference... *

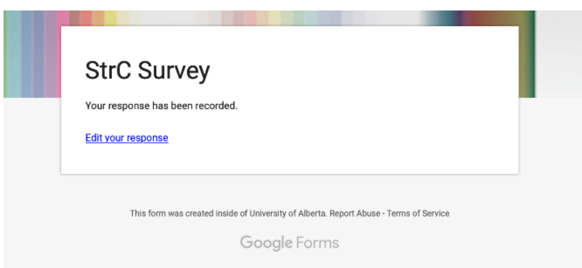
	1	2	3	4	5	
High	◉	○	○	○	○	None

Send me a copy of my responses.

BACK SUBMIT Page 9 of 9

Never submit passwords through Google Forms.

Last step before submission is to complete basic demographic information



StrC Survey

Your response has been recorded.

Edit your response

This form was created inside of University of Alberta. Report Abuse - Terms of Service

Google Forms

The following are the questions contained in the questionnaires:

1. *(1.0)* Participants basic information.
   - *1.1.* “Please select the option that best defines your profession” (scientist, designer, other);
   - *1.2.* “Please specify your main disciplinary area”;
   - *1.3.* “Choose all that apply” (scholar/researcher, practitioner, student, other):
   - *1.4.* “Years of experience in your main disciplinary area;”
   - *1.5.* “Your highest degree achieved” (PhD, Master, Bachelor, other);
   - *1.6.* “Affiliation” (University/college, company, independent);
     - *1.6.1.* “Name of Affiliation;”
     - *1.6.2.* “Name of Area, Division or Department;”
     - *1.6.3.* “Location” (City, Country);
   - *1.7.* “You consider your knowledge on biomimicry / biomimetic design...” (linear scale);
   - *1.8.* “You consider your knowledge on biophotonics and / or structural colour –physics’ light interference...” (linear scale).

2. *(2.1)* Main Questionnaire for Scientist.
   - *2.1.1.* “The StrC current version is a beta version for testing purposes only, fed with a small dataset yet to be populated in the future. A full developed tool would collect thousands of items from scientific repositories (museums, collections, and other scientific databases). This being considered, StrC is a suitable concept for developing a comprehensive research tool” (linear scale; “Add any comments or thoughts you may have”);
   - *2.1.2.* “The taxonomic content of StrC (levels, categories and items) is correctly organized” (linear scale; “Add any comments or thoughts you may have”);
   - *2.1.3.* “Would you be interested in contributing with scientific data to the StrC database? (e.g. adding species, photographs, publications, updates, amendments or other details)” (multiple choice: yes, maybe, no), “What would you contribute with?”;
   - *2.1.4.* “The mechanism, structure and characteristics of structural colour –light interference– in the species profile pages are well described, illustrated and accurate” (linear scale; “Add any comments or thoughts you may have”);
   - *2.1.5.* “The widgets: (phylogeny, homology, research map, evolutionary disruptions) are useful to initiate / expand scientific discussions among peer scientists (e.g. evolutionary convergences, presumable connections between colours and functions, aposematism, crypsis, etc.)” (linear scale), “What discussion topics do you think could be generated from using the widgets?”;
   - *2.1.6.* “What other data visualization tools would you like to see in the StrC environment?” (5 check box options + “other”);

2.1.7. "What features you consider appealing to designers looking for scientific information on structural colour?" (4 check box options + "other"), "Add any additional comments you may have on StrC features";

2.1.8. "What areas to apply biomimetic design on structural colour do you see with potential?" (6 check box options + "other");

2.1.9. "StrC can be also a communication tool for sharing, discussing and get in contact with the scientific and design community interested in biomimicry applications" (linear scale), "Would you use StrC for sharing, discussing and keeping contact?" (multiple choice: yes, maybe, no), "Add any additional comments you may have on using StrC as a communication tool";

2.1.10. "Rank how the widgets would serve best to speculate with existing and/or new theories and hypothesis" (multiple choice grid with 4 options);

2.1.11. "The collection of cases grouped by colour hue may showcase evidence on patterns, convergences, and evolutionary similarities. What observations can you make about particular hues based on the number of cases? (e.g. the abundance of structural blue vs. structural red)"

2.1.12. "Please provide additional feedback, comments and suggestions about the design and content of the following StrC features:" (4 text box options, 1 linear scale), "Add any additional comments you may have on using the colour picker function"

2.2. *(2.2)* Main Questionnaire for Designers and Other Participants.

2.2.1. "The StrC current version is a beta version for testing purposes only, fed with a small dataset yet to be populated in the future. A fully developed tool would collect thousands of items from scientific repositories (museums, collections, and other scientific databases). This being considered, StrC is a suitable concept for developing a comprehensive research tool" (linear scale);

2.2.2. "StrC provides access to scientific information and knowledge in a very effective and intuitive way to inspire biomimetic ideas" (linear scale), "Add any additional comments you may have";

2.2.3. "StrC provides elements to better understand the concept of structural colour and facilitates access to scientific information on structural colour" (linear scale), "Add any additional comments you may have";

2.2.4. "After experimenting with StrC I am interested (or more interested) in doing more research on the subject of structural colour" (linear scale), "Add any additional comments you may have";

2.2.5. "After experimenting with StrC I am interested (or more interested) in finding new biomimetic applications for structural colour" (linear scale), "Add any additional comments you may have";

2.2.6. “What features do you consider appealing to designers looking for scientific information on structural colour?” (4 check box options + “other”);

2.2.7. “What areas to apply biomimetic design on structural colour do you see with potential?” (6 check box options + “other”);

2.2.8. “StrC can be also a communication tool for sharing, discussing and get in contact with the scientific and design community interested in biomimicry applications” (linear scale), “Would you use StrC for sharing, discussing and keeping contact?” (multiple choice: yes, maybe, no), “Add any additional comments you may have on using StrC as a communication tool”;

2.2.9. “Please provide additional feedback, comments and suggestions about the design and content of the following StrC features:” (3 text box options, 1 linear scale), “Add any additional comments you may have on using the colour picker function”;

2.2.10. “The StrC widgets tested are "mock up" versions, currently simulated in this prototype. Future full developed versions of the individual widgets will make a big contribution to the StrC” ” (linear scale); “Please provide additional feedback, comments and suggestions about the design of the Homology widget”, “Please provide additional feedback, comments and suggestions about the design of the Phylogeny widget”, “Please provide additional feedback, comments and suggestions about the design of the Research Map widget”, “Please provide additional feedback, comments and suggestions about the design of the Evolutionary Disruptions widget.”

7.1.8 Email Invitations Templates

StrC: A Tool for Research to Connect Nature and Design

Letter of Invitation (Email content) – Scientists Living Light Network

Dear Member of the Living Light Network,

I am conducting a research study from the University of Alberta, which consists in doing a prototype testing of a digital interface online [strc.online]. The interface is intended to facilitate access to available scientific information on structural colour to designers interested in biomimetic applications. The purpose of this study is to test the potential use of this interface as a tool for research beyond a prototype stage, and the outcomes may help connecting design with scientific knowledge, and scientists with design opportunities. As a member of the international community of expert scientists dedicated to investigate biophotonics, your contribution to this study would be highly appreciated. If you are interested in participating, please visit this link: **http://strc.online/study,** and follow the steps that will guide you to explore the complete digital environment. You will find also a step-by-step guidelines document attached to this email. At the end of the experience, **please fill a brief survey to provide feedback: StrC.online/survey.**

Please feel free to share this invitation and poster attached among your colleagues and peers. If you have any question, please don't hesitate in contacting me.

Thank you in advance!

Regards,

Carlos Fiorentino, Principal Investigator, PhD Candidate in Human Ecology,
carlosf@ualberta.ca
1 780 707 7541
Department of Human Ecology, 302 Human Ecology Building,
University of Alberta, Edmonton, T6G 2N1

If you have any questions about your rights as a participant, please contact the University of Alberta Research Ethics Board at 1.780.492.2615 Re: Pro#00085144

StrC: A Tool for Research to Connect Nature and Design

Letter of Invitation (Email content) – Scientists

Dear Scientist,

I am conducting a research study from the University of Alberta, which consists in doing a prototype testing of a digital interface online [strc.online]. The interface is intended to facilitate access to available scientific information on structural colour to designers interested in biomimetic applications. The purpose of this study is to test the potential use of this interface as a tool for research beyond a prototype stage, and the outcomes may help connecting design with scientific knowledge, and scientists with design opportunities. Your contribution to this study would be highly appreciated. If you are interested in participating, please visit **http://strc.online/study,** and follow the steps that will guide you to explore the complete digital environment. You will find also a step-by-step guidelines document attached to this email. At the end of the experience, **please fill a brief survey to provide feedback: StrC.online/survey.** Please feel free to share this invitation and poster attached among your colleagues and peers. If you have any question, please don't hesitate in contacting me.

Thank you in advance!

Regards,

Carlos Fiorentino, Principal Investigator, PhD Candidate in Human Ecology,
carlosf@ualberta.ca
1 780 707 7541
Department of Human Ecology, 302 Human Ecology Building,
University of Alberta, Edmonton, T6G 2N1

If you have any questions about your rights as a participant, please contact the University of Alberta Research Ethics Board at 1.780.492.2615 Re: Pro#00085144

StrC: A Tool for Research to Connect Nature and Design

Letter of Invitation (Email content) – Design Practitioners, Design Scholars, and Other

Dear Colleague,

I am conducting a research study from the University of Alberta, which consists in doing a prototype testing of a digital interface online [strc.online]. The interface is intended to facilitate access to available scientific information on structural colour to designers interested in biomimetic applications. The purpose of this study is to test the potential use of this interface as a tool for research beyond a prototype stage, and the outcomes may help connecting design with scientific knowledge, and scientists with design opportunities. Your contribution to this study would be highly appreciated. If you are interested in participating, please visit **http://strc.online/study,** and follow the steps that will guide you to explore the complete digital environment. You will find also a step-by-step guidelines document attached to this email. At the end of the experience, **please fill a brief survey to provide feedback: StrC.online/survey.**

Please feel free to share this invitation and poster attached among your colleagues and peers. If you have any question, please don't hesitate in contacting me.

Thank you in advance!

Regards,

Carlos Fiorentino, Principal Investigator, PhD Candidate in Human Ecology,
carlosf@ualberta.ca
1 780 707 7541
Department of Human Ecology, 302 Human Ecology Building,
University of Alberta, Edmonton, T6G 2N1

If you have any questions about your rights as a participant, please contact the University of Alberta Research Ethics Board at 1.780.492.2615 Re: Pro#00085144

StrC: A Tool for Research to Connect Nature and Design

Letter of Invitation (Email content) – Design Practitioners, Scholars and Scientists from the Biomimicry Network

Dear Biomimic,

I am conducting a research study from the University of Alberta, which consists in doing a prototype testing of a digital interface online [strc.online]. The interface is intended to facilitate access to available scientific information on structural colour to designers interested in biomimetic applications. The purpose of this study is to test the potential use of this interface as a tool for research beyond a prototype stage, and the outcomes may help connecting design with scientific knowledge, and scientists with design opportunities. As a member of the international biomimicry community, your contribution to this study would be highly appreciated. If you are interested in participating, please visit **http://strc.online/study,** and follow the steps that will guide you to explore the complete digital environment. You will find also a step-by-step guidelines document attached to this email. At the end of the experience, **please fill a brief survey to provide feedback: StrC.online/survey.** Please feel free to share this invitation and poster attached among your colleagues and peers. If you have any question, please don't hesitate in contacting me.

Thank you in advance!

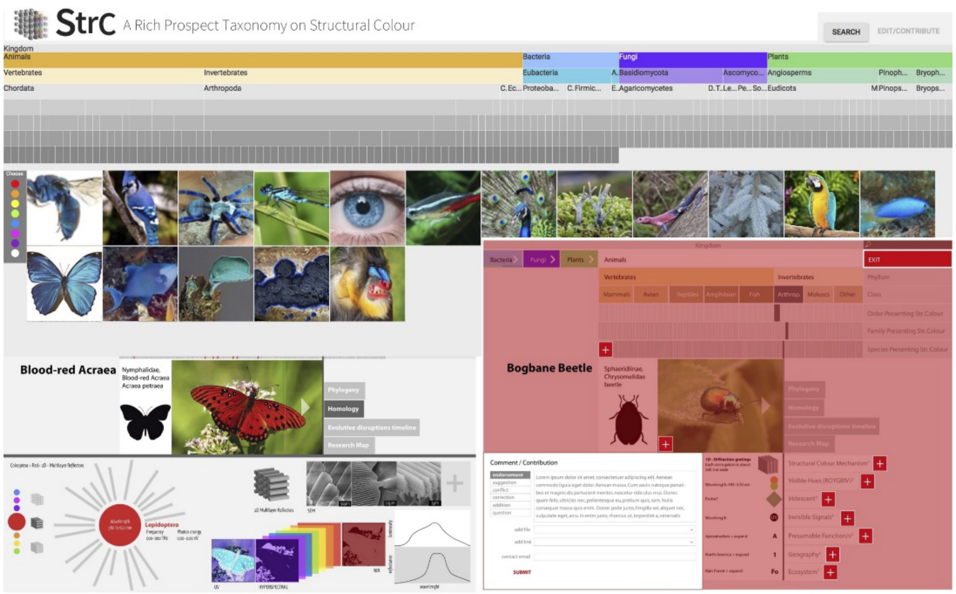
Regards,

Carlos Fiorentino, Principal Investigator, PhD Candidate in Human Ecology,
carlosf@ualberta.ca
1 780 707 7541
Department of Human Ecology, 302 Human Ecology Building,
University of Alberta, Edmonton, T6G 2N1

If you have any questions about your rights as a participant, please contact the University of Alberta Research Ethics Board at 1.780.492.2615 Re: Pro#00085144

7.1.9 Study Digital Poster

Invitation to participate in the study
StrC: A Tool for Research to Connect Nature and Design



Screenshots obtained from mock ups and work-in-progress versions of StrC interface

A research team from the University of Alberta is doing a prototype testing of a digital interface online [strc.online]. The purpose of this study is to test the potential use of this interface as a tool for research beyond a prototype stage, connecting design with scientific knowledge, and scientists with design opportunities. We are inviting designers and scientists from the international community interested in applying structural colour for biomimetic innovation to participate in this study. Participants will be provided with access to the StrC interface available on line and will be asked to explore the complete digital environment, with a set of guiding questions/cues, as well as to fill a brief survey to provide feedback on the experience.

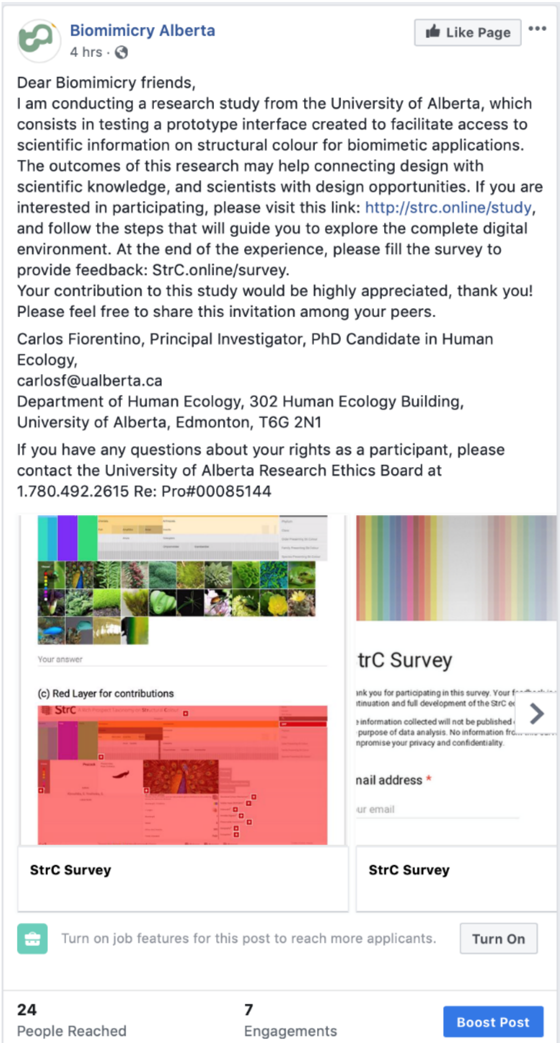
If you are interested, please contact the principal investgator,
PhD Candidate Carlos Fiorentino:
carlosf@ualberta.ca

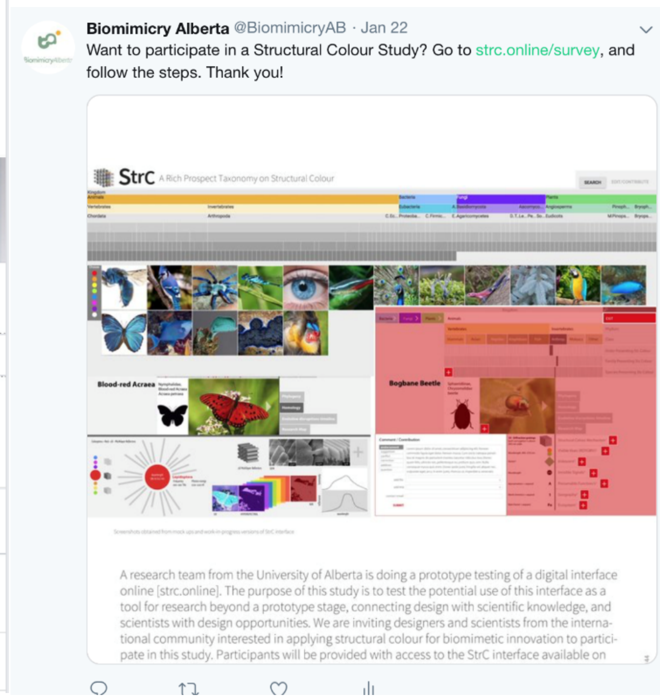
StrC

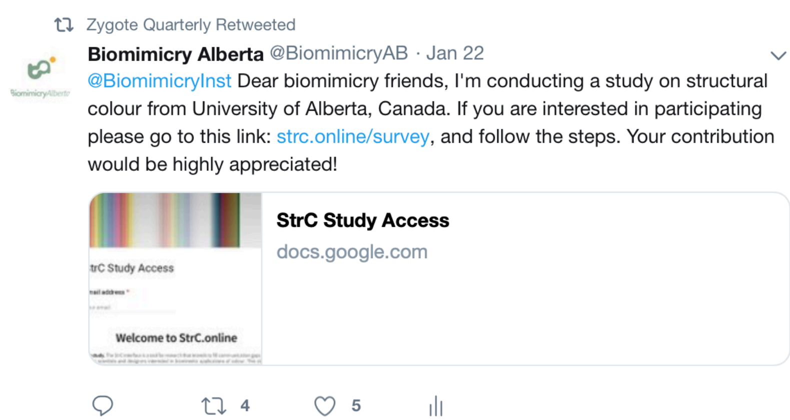
7Vortex ASKNATURE BiomimicryAlberta

Study approved by University of Alberta Research Ethics Board Pro#00085144

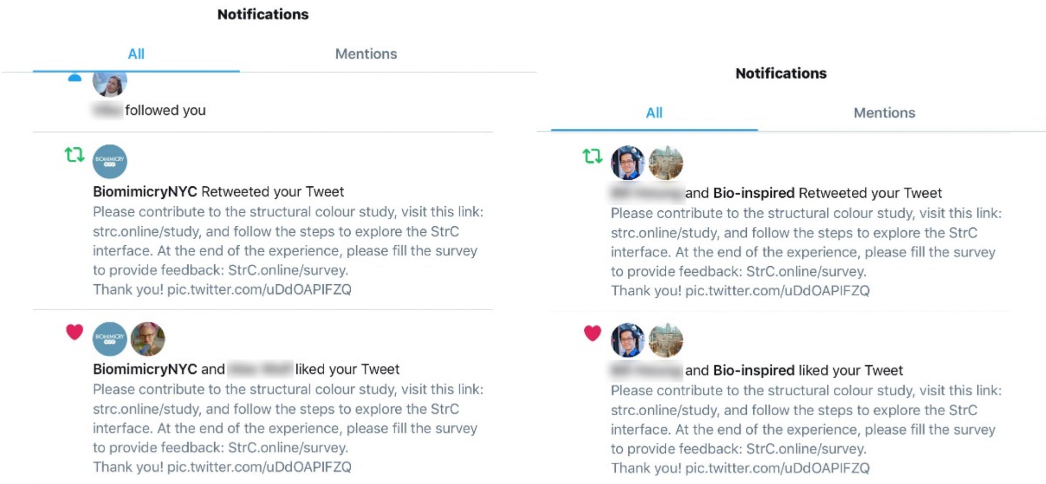
7.1.10 Social Media Posts



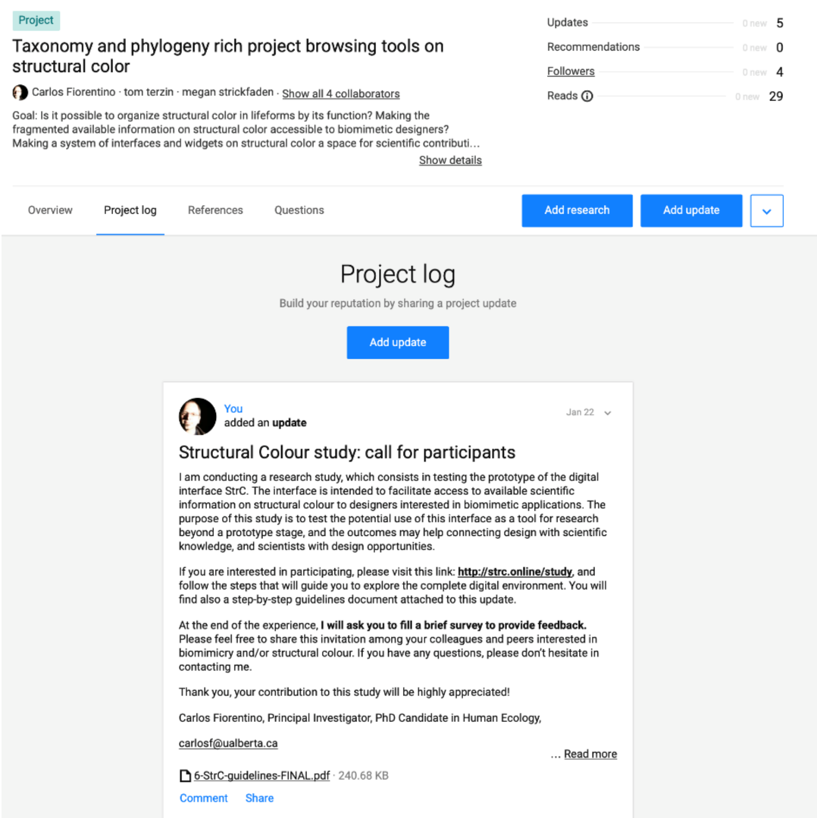




Facebook and tweeter calls were reposted and retweeted among several biomimicry networks



Facebook and tweeter calls were reposted and retweeted among several biomimicry networks



Invitation to StrC project followers and other researchers in Research Gate

7.1.11 Additional Post-Survey Interview Questions

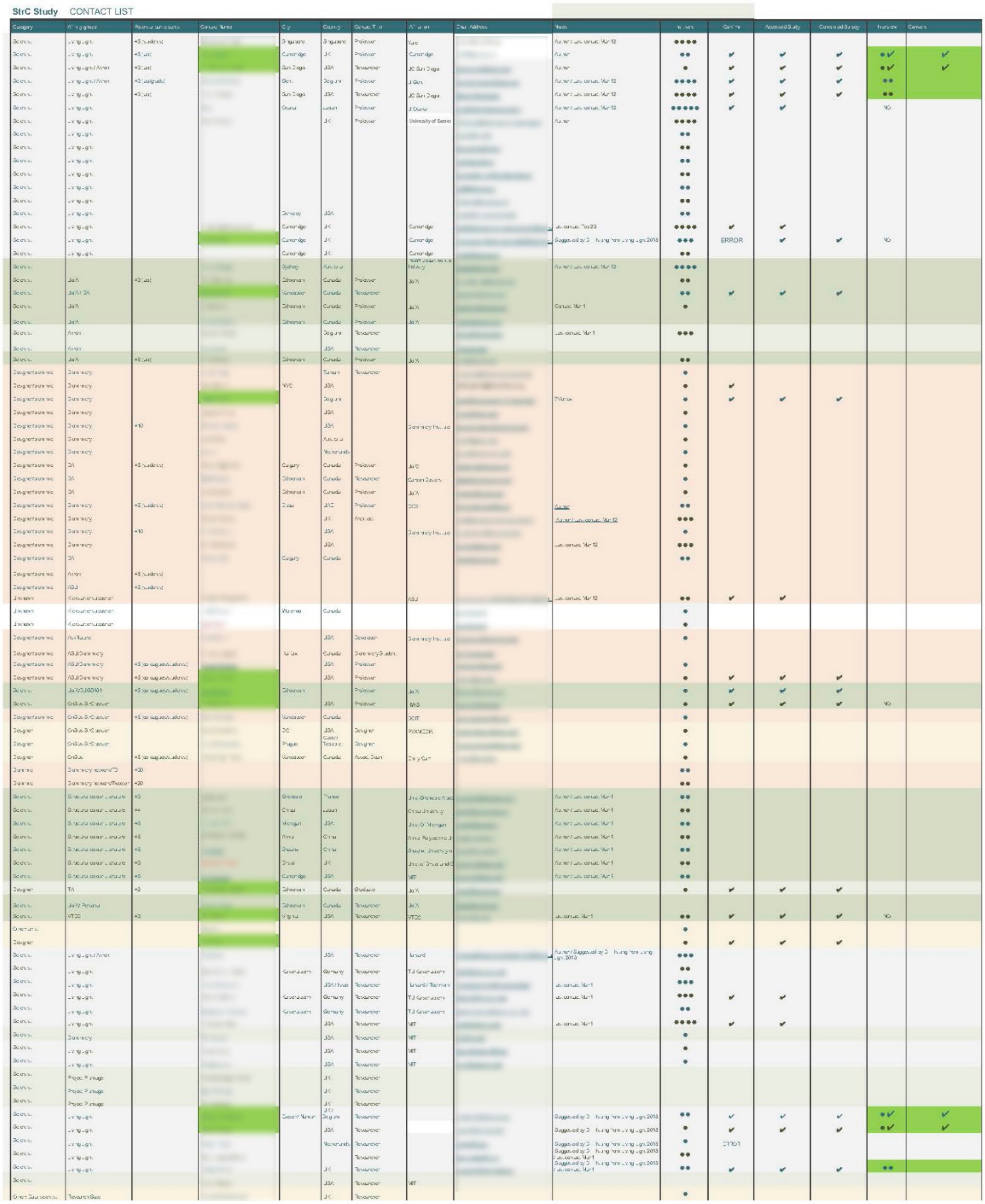
INTERVIEW QUESTION #1 –"Full agreement on the number, variations and/or combinations of structural colour mechanisms in nature is still under scientific debate. In your view, what are the constrains or limitations that science faces to arrive to a clear classification and categorization of structural colour?"

INTERVIEW QUESTION #2 –"How relevant is is to identify and classify structural colour cases by function (e.g. crypsis, aposematism, mating, etc.) rather than, for instance, wave length or colour hues?"

INTERVIEW QUESTION #3 –"It is possible to detect structural colour convergences (e.g. similar mechanism for a similar function) across species from different kingdoms, different ecosystems and geolocations? Would this be relevant to better understand structural colour purposes and possibilities for

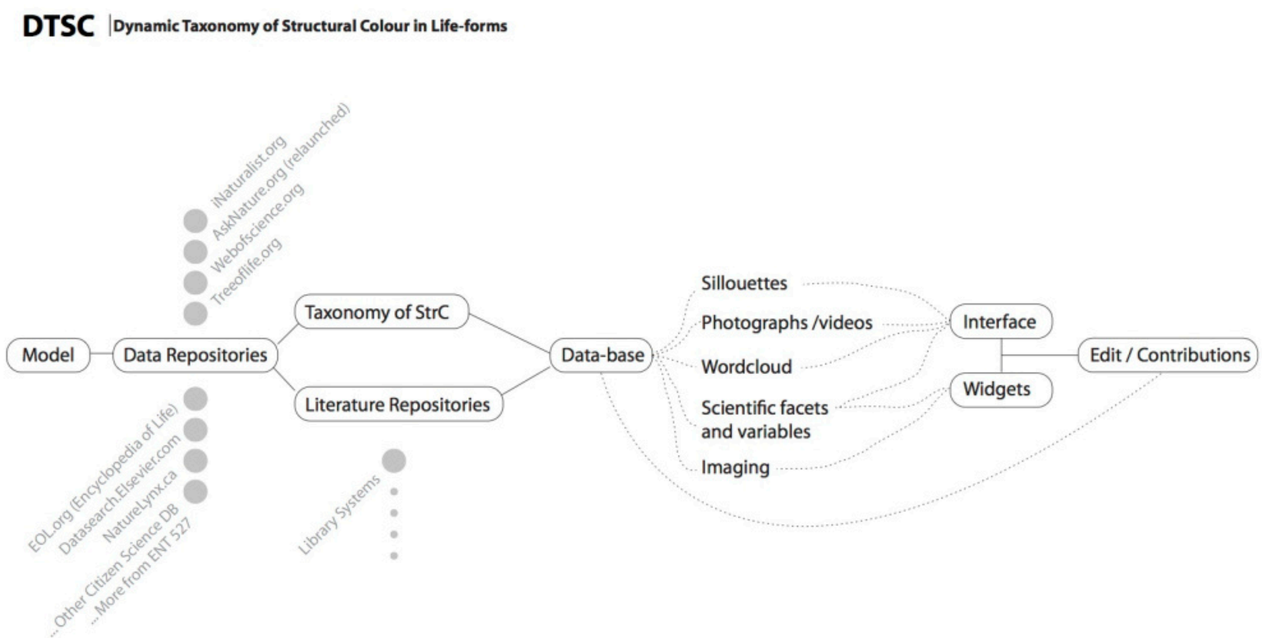
INTERVIEW QUESTION #4 –"Can you offer a hypothesis or a theory on why blue pigment is rare in nature, and blue structural colour so abundant in comparison? Would this be a clue to understand the origin and evolution of structural colour phenomenon?"

7.1.12 Enrollment Follow-up Spreadsheet

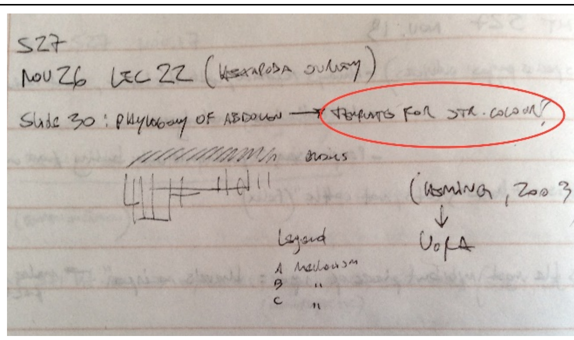
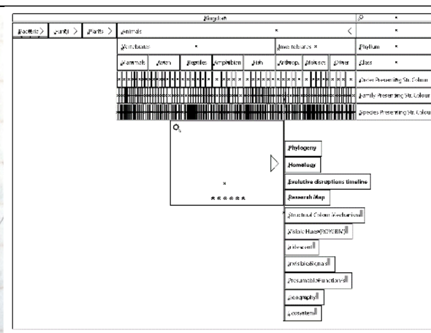

StrC Study CONTACT LIST

7.2. StrC Design and Developing Process Materials

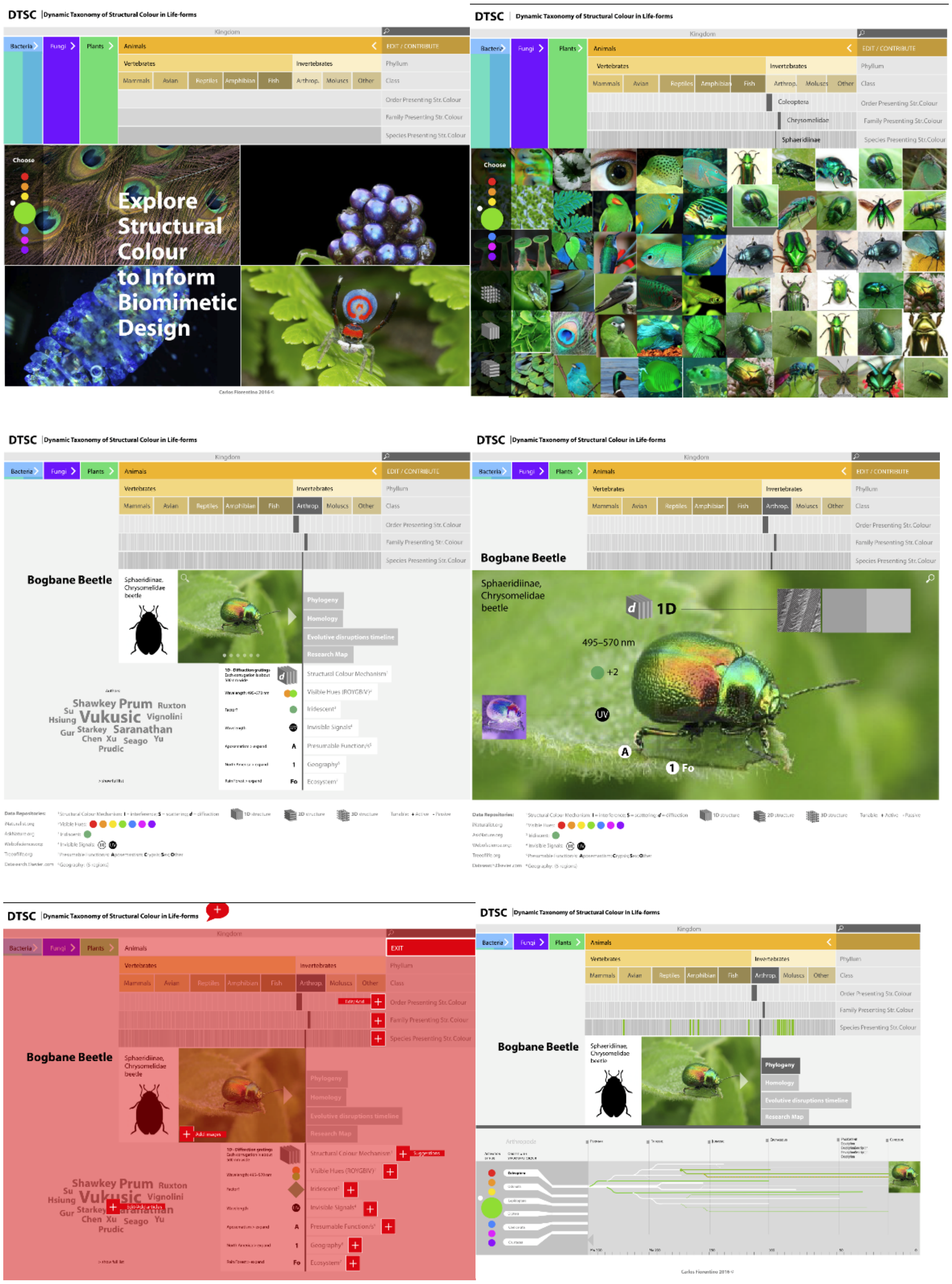
7.2.1 Project Structure Initial Diagram



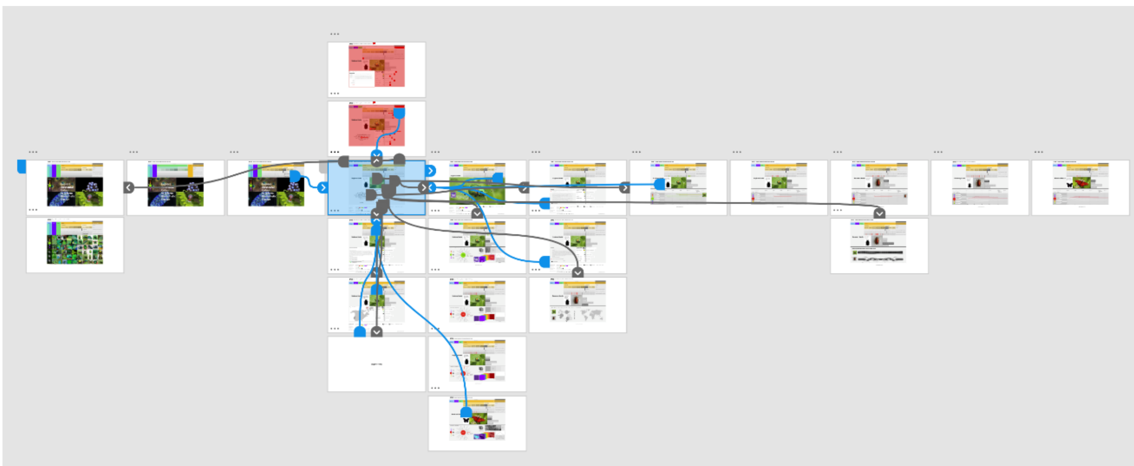
7.2.2 Initial Ideas and Mockup Version

Initial ideas and sketches

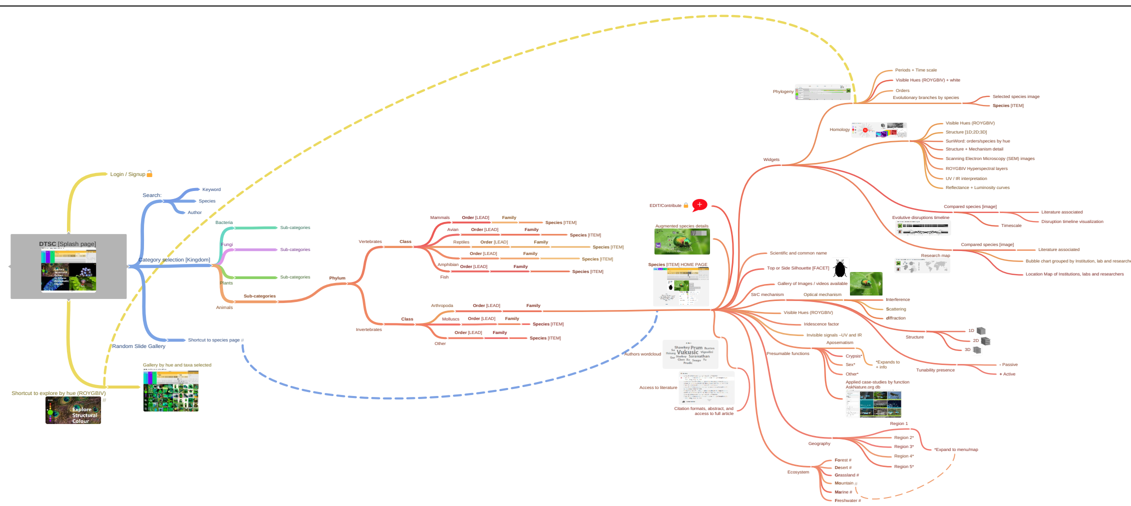


Screenshots of initial mockup version developed in Adobe Illustrator and published in Adobe XD.



Adobe XD organization of mockup navigation.

7.2.3 StrC Site Flow Diagram



Original navigation flow plan for the site created in “Coggle.”

7.2.4 Initial Dataset Preparation

Categories	Scientific name: Species	Family	Common name	Sillouette	Pictures	Wordcloud (authors) 1: #List of articles 2	#Detail 3	#Abstract 4	Structural Colour: Mechanism: Interference	Scattering	diffraction	Description	Structure: 1D	2D	3D	Tunable: Active	Passive	Hue/s: ROYGVIB	Wavelenght nm	Iridescence: Y/N	Factors
Invertebrate	Chrysochus auratus	Chrysomelidae	Bogbane Beetle			Gold bugs and beyond: a review of iridescence and structural colour mechanisms in beetles (Coleoptera).	Seago, A. E., Brady, P., Vigneron, J.-P., & Schultz, T. D. (2009). Gold bugs and beyond: a review of iridescence and structural colour mechanisms in beetles	Members of the order Coleoptera are sometimes referred to as 'living jewels', in allusion to the strikingly diverse array of iridescence mechanisms and			d	Diffraction grattings: Each corrugation is about 500 nm wide					✔		495-570		r = angle=
Invertebrate	Chrysina aurigans	Scarabaeidae	Rosemary Beetle			Qualitative correlation between structural chirality through the cuticle of Chrysina aurigans scarabs and left-handed circular polarization of the reflected light	[2014] M. Hernández-Jiménez, D. E. Azofeifa, E. Libby, C. Barboza-Aguilar, Á. Solís, L. Arce-Marenco, I. García-Aguilar, A. Hernández, and W. E. Vargas. Optical	Measured reflection spectra from elytra of C. aurigans scarabs are reported for wavelengths between 300 and 1100 nm. They show a broad reflection band for			d	Ripple multilayer structure of the cuticle					✔		525 to 950		r = angle=
Invertebrate > arthropoda > odonata			Dragonfly																		
Invertebrate > arthropoda > hymen		Chrysididae	Blue Cuckoo Wasp																		
Invertebrate	Acraea petrae	Nymphalidae	Blood-red Acraea			Anatomically diverse butterfly scales all produce structural colours by coherent scattering	[2006] Prum, RO; Quinn, T;Torres, RH, Journal of Experimental Biology; http://jeb.biologists.org/content/209/4/748.short		I			Multilayer interference. Light reflected from the overlapping lamella that build the longitudinal					✔			N	r = angle=
Invertebrate	Avicularia laeta	Theraphosidae	Blue Tarantula			Tarantula-Inspired Noniridescent Photonics with Long-Range Order	[2016] Bor-Kai Hsiung, Radwanul Hasan Siddique, Lijia Jiang, Ying Liu, Matthew D. Shawkey, Todd A. Blackledge	Photonic structures with long-range order are inherently iridescent, suggesting by current theory. Contrary to this paradigm and inspired by biological	I			Quasi-ordered and multilayer interference					✔		450	N*	r = angle=
Invertebrate	Sapphirina	Sapphirinidae	Sea Saphire Copepod			The Structural Basis for the Brilliant Colors of the Sapphirinid Copepods and the Neon Tetra Fish	Dvir Gur1, Ben Leshem2, Maria Pierantoni1, Viviana Farstey3, Dan Oron2, Steve Weiner1, Lia Addadi1, 1Dept. of Structural Biology, Weizmann Institute of	In animals colors are produced by either pigment coloration or structural colors. Structural colors are caused by the interaction of light with structures that have		S		Photonic hexagon shaped crystals 70nm thick, layers of cytoplasm between the crystal				✔					r = angle=
Vertebrate >	Pavo Cristatus	Phasianidae	Peacock			Effect of Macroscopic Structure in Iridescent Color of the Peacock Feathers	Yoshioka, S., & Kinoshita, S. (2002). Effect of Macroscopic Structure in Iridescent Color of the Peacock Feathers. Forma, 17, 169–181	We have performed the structural and optical studies on the iridescent peacock feathers. The periodic structure of the	I	S		Periodic array of melanin granule rods produce optical interference and scattering among the									r = angle=
Vertebrate >	Cyanocitta cristata	Corvidae	Blue jay																		
Vertebrate >	Paracheirodon innesi	Characidae	Neon Tetra Fish																		
Vertebrate >	Homo Sapiens	Hominidae	Human (blue eyes)																		

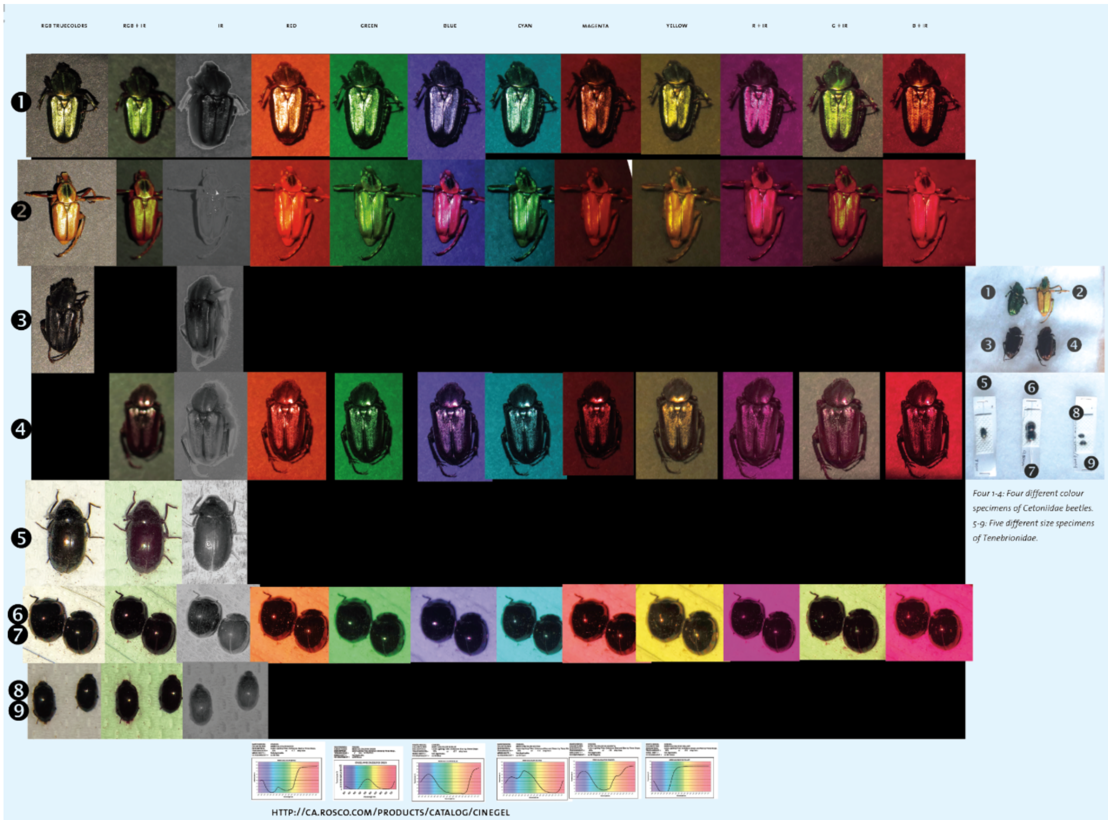
1: Collect main author's names from articles related in repositories/database> e.g. on "Chrysochus auratus" if they include "structural color" "iridiscent" "diffraction" " light interference"
2: Collect articles related in repositories/database> e.g. on "Chrysochus auratus" if they include "structural color" "iridiscent" "diffraction" " light interference"
3: Show citation details of selected document if available from repossitories/database
4: Show abstract of selected document if available from repossitories/database
5: Dominant hue
6: Regions 1-Americas 2-Europe 3-Africa 4-Asia 5-Oceania

Invisible signals: UV	IR	Presumable functions (Description (blurb and refs)): Aposematism	Crypsis	Sexual	Other	Geography: Map location 6: Region 1	Region 2	Region 3	Region 4	Region 5	Ecosystem (Map locations): Forest	Desert	Grassland	Mountain	Marine	Freshwater	Phylogeny: Hue 5	Order	Period	Image
		A		S		Americas					Fo		Gr	Mo				Coleoptera	Cretaceus to present	
						Americas	Europe				Fo		Gr					Coleoptera		
																		Odonata		
																		Hymenoptera		
UV				S				Africa			Fo			Mo				Lepidoptera		
UV					O				Asia		Fo							Chellicerata		
UV	IR					Americas		Africa	Asia						Ma			Crustacea		
				S				Africa	Asia	Oceania								Avian		
																		Avian		
																		Fish		
																		Mammal		

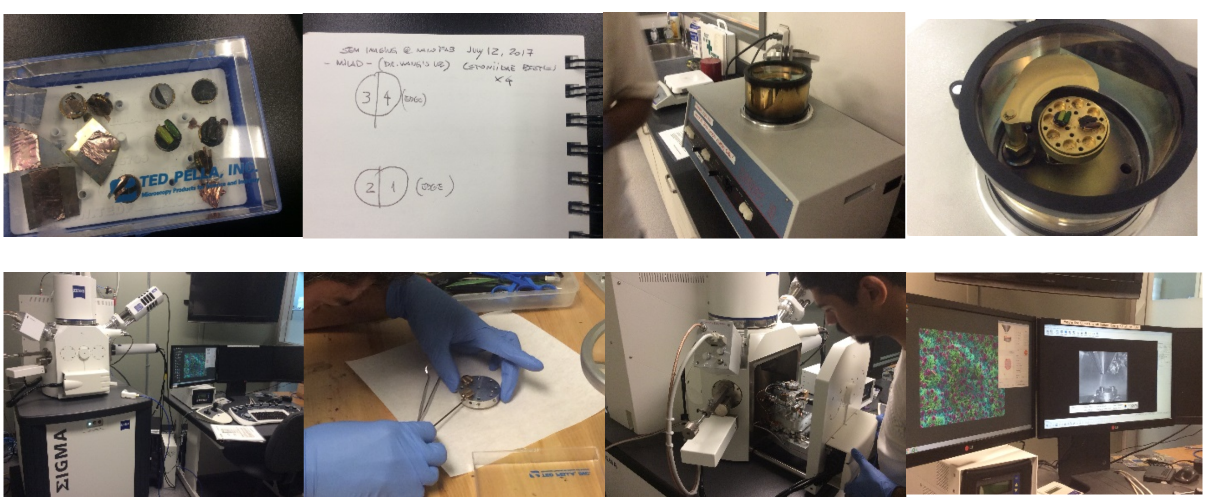
WIDGETS (see separate document for overview) — Homology/Analogy: Hue	Structure	Wavelenght	Frequency	Photon Energy	Mechanism	Hyperspectral layers	SEM	Reflectance	luminosity	Evolutive disruptions timeline	Research map
		495-570 nm	526-606 Thz	217-250 eV	1D Diffraction Gratings	✔		(curve chart)	(curve chart)	✔	✔
		525 to 950 nm									
		450 nm				✔		(curve chart)	(curve chart)		
						✔		(curve chart)	(curve chart)		

Initial dataset created in Microsoft Excel to populate the StrC database through the API backend interface.

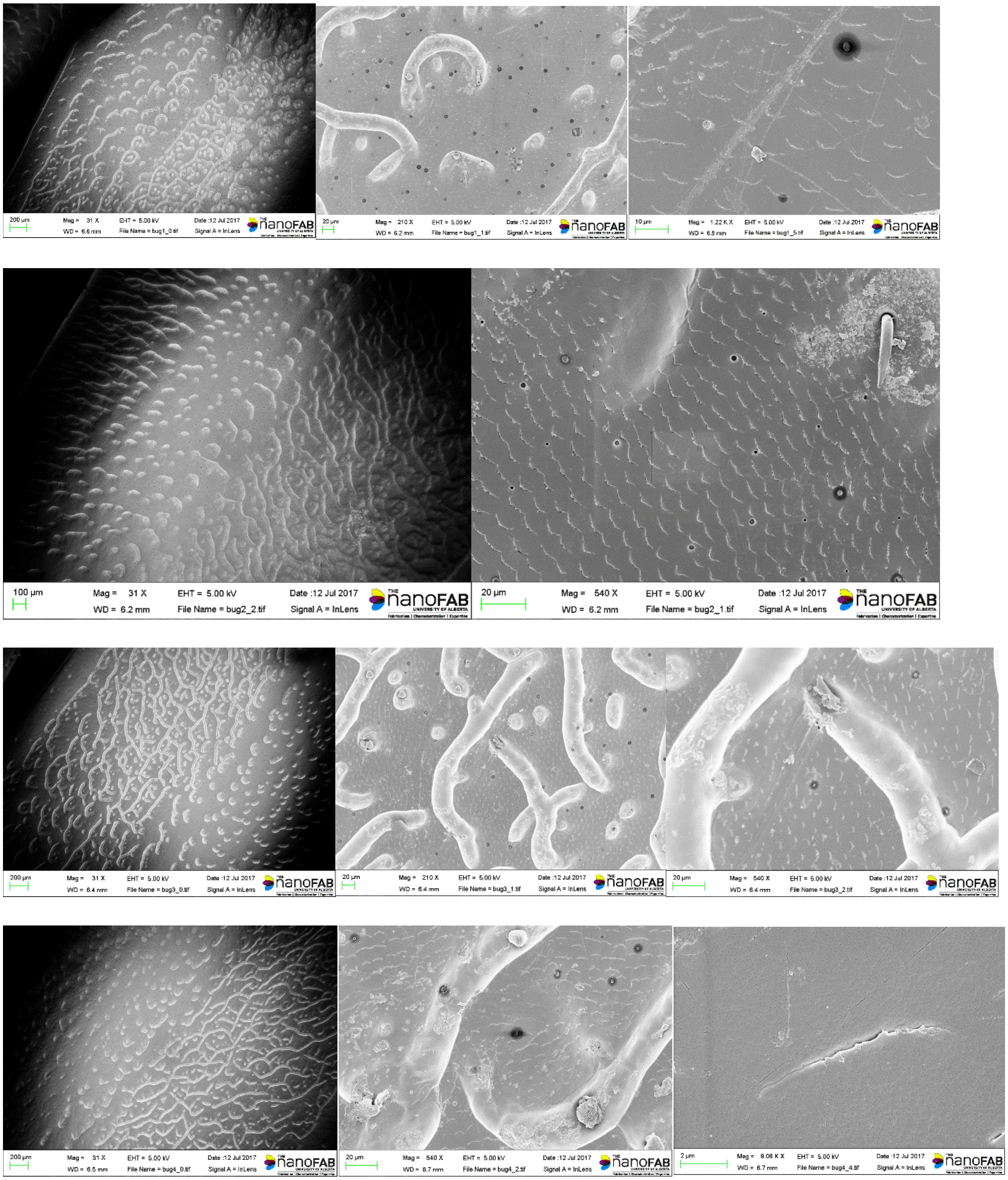
7.2.5 SEM and Hyperspectral Imaging Exploration



Testing of infrared and hyperspectral simulation with Foveon sensor photography.

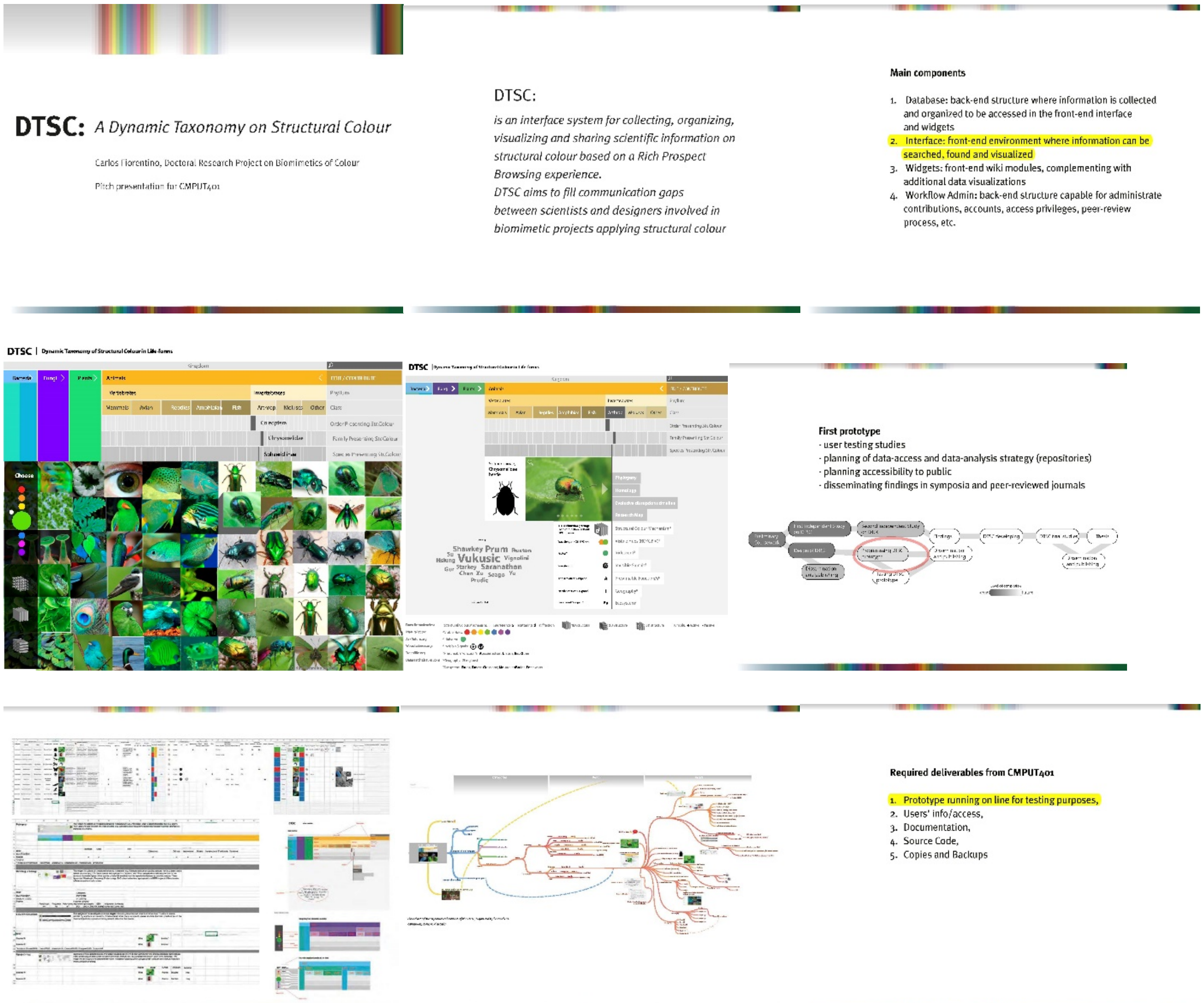


Preparation steps for Scanning Electron Microscopy (SEM) to detect structural colour nanostructure details in specimens from Dr. Terzin's entomology collection.



SEM images collected in the testing.

7.2.6 Information Materials for Developers



Slideshow delivered to Computing Science CMPUT 401 inviting to contribute to StrC (DTSC) development.

DTSC –Dynamic Taxonomy on Structural Colour: A Visual Interface to Bridge Science and Design Innovation

Carlos Fiorentino (PhD Human Ecology, MDes Art & Design)
Supervision: Dr. Megan Strickfaden, Dr. Anne Bissonnette (Human Ecology, U of A)
Scientific Advisor: Dr. Tomislav Terzin (Biological Sc. U of A, Augustana)

The Dynamic Taxonomy on Structural Colour –DTSC is a browsing interface, conceptually similar to any webpage browser, with the capacity to find, arrange and visualize scientific information (metadata) about species (animals, plants, etc.) showing structural coloration.[1] Based on a Rich Prospect Browsing experience,[2] users –designers and scientists– should be able to find, select, and customize their search results, inviting to more exploration and eventual contributions. The initial dataset for such a dynamic tool, will be provided in a spreadsheet, which includes images and data about a selection of species to populate a database. This information is organized in a scientific taxonomical manner, with main categories, sub categories, facets, details, etc. The main tool for initiate any query is a "colour picker" available on the home page, however the user should be able to also navigate the database by clicking on categories, individual species, or typing keywords on a search engine. The way a CMPUT 401 team could contribute to this project is by developing a working prototype of the DTSC interface for testing purposes.

An example of how the user of the DTSC interface may find basic information can be described as follows:

1- The user opens the interface home page and a main modular menu shows a taxonomic arrangement of options (fig.1a), a colour picking tool (fig.1b), and a search engine field (fig.1c).
2- The user picks a colour hue from the color picker and the interface prompts a collection of images related to that hue, collected from the available database (fig.2).
3- The user picks one image (one species) and the interface prompts a "page profile" of this particular species with all the scientific data available about it (fig.3).
4- There is a number of possibilities from this point of the process that may be offered to the user in the future (access to more data in scientific repositories, access to developed visualizations and widgets, review and contribution tools, etc.); for now achieving a basic navigational experience in a first prototype is aimed for CMPUT 401.

Structural colour is an exciting emerging area within biomimetic design (biomimicry[3]) and scientific innovation. Scientists and designers alike are embarked in research projects

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[1] Structural Colour –in physics "light interference"– which is a way of achieving colour without relying on pigmentation or chemical coloration processes, but rather by adding "information" to material surfaces at the nano-scale. In nature Structural Colour is observed in an abundant number of species across animals, plants, fungi and bacteria.

[2] A Rich Prospect Browser is an experimental interface, in which the home page displays a visual representation of every item in a given collection, combined with tools for manipulating the display.

[3] Biomimicry is an emerging design discipline that studies "nature's best ideas" with the purpose of emulating them to address human problems by design. Biomimicry is "an approach to innovation that seeks sustainable

Project brief document.

that may provide important advancements on materials, new products and communication technology based on structural colour observed in nature. DTSC may contribute and facilitate the communication between scientists and designers involved in current biomimetic projects, as well as inspire new ones.

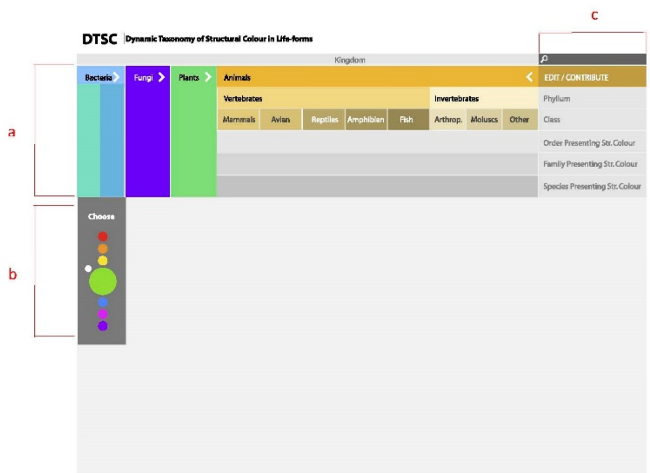


Fig.1: DTSC home page shows a main modular menu organized as a biological taxonomy: kingdoms, phylum, class, order, family and species (a), a colour picking tool to select a hue (b), and a search engine field (c).

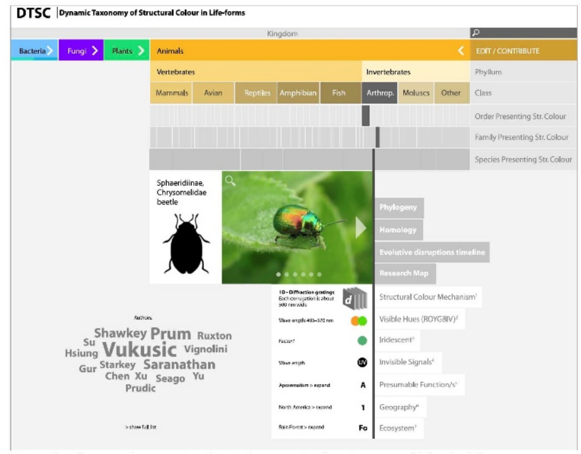
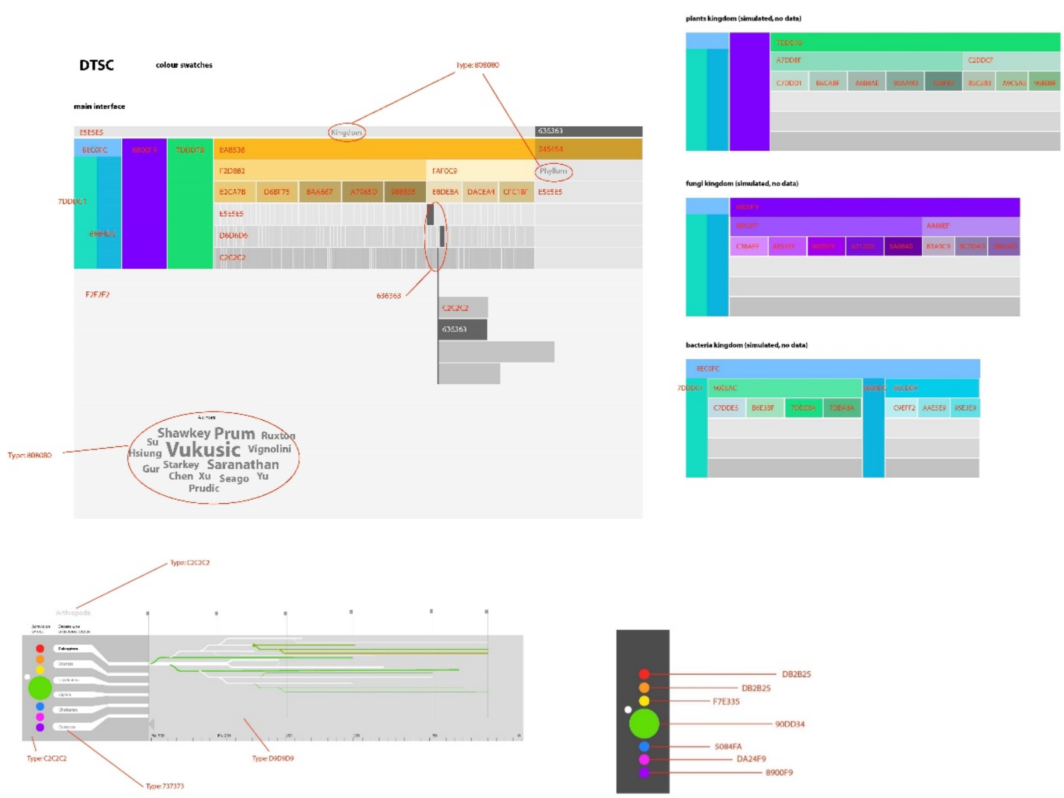


Fig.3: When the user picks one species, the interface prompts a "species page profile" with all the scientific data available about it:structural colour mechanisms, visible hues, iridescence, UV, IR, functions, location and bibliography available, as well as other options to be developed in the future (e.g. phylogeny, homology, timeline and maps visualizations).

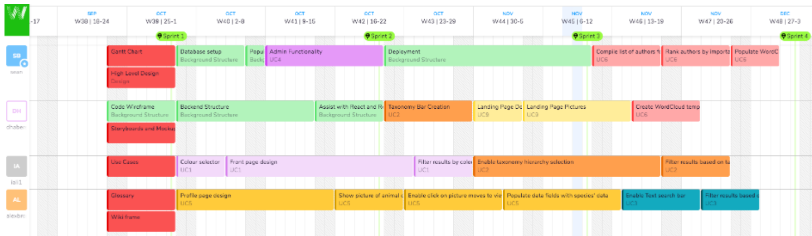
MOCKUP VERSION: https://xd.adobe.com/view/db3f8da5-fc16-4a54-b75a-68ff8eba2f9e/

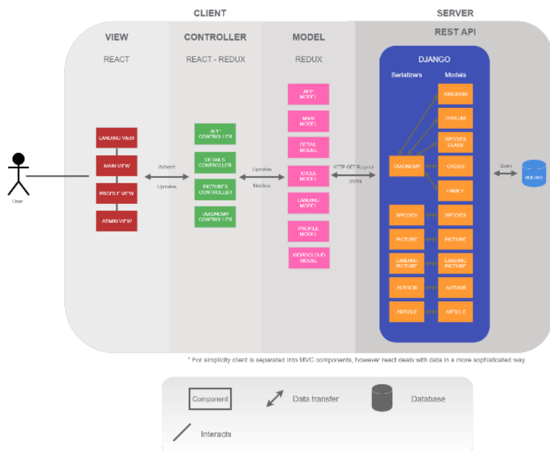
FLOWCHART OF THE PROJECT:
https://carlosfiorentino.files.wordpress.com/2016/11/flow-diagram-copy.jpg
(password protected: carlos)

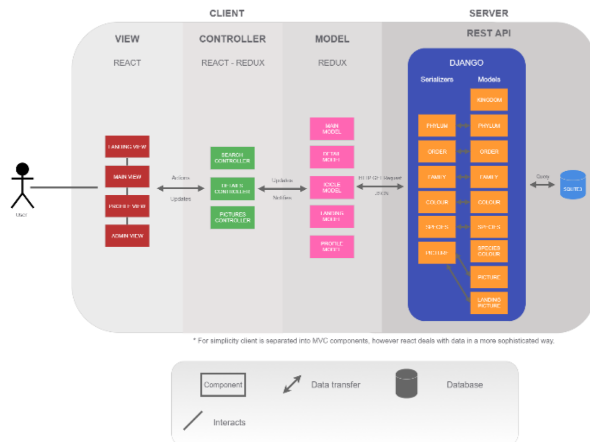
FLOWCHART OF DTSC INTERFACE CONTENT:
https://carlosfiorentino.files.wordpress.com/2016/11/dtsc_flowchart.pdf
(password protected: carlos)

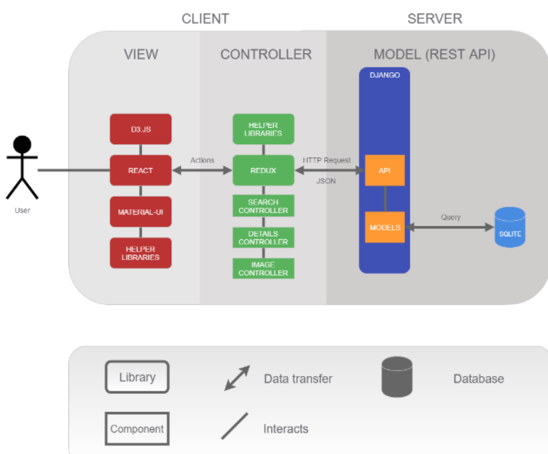


Colour codes guideline for developers.

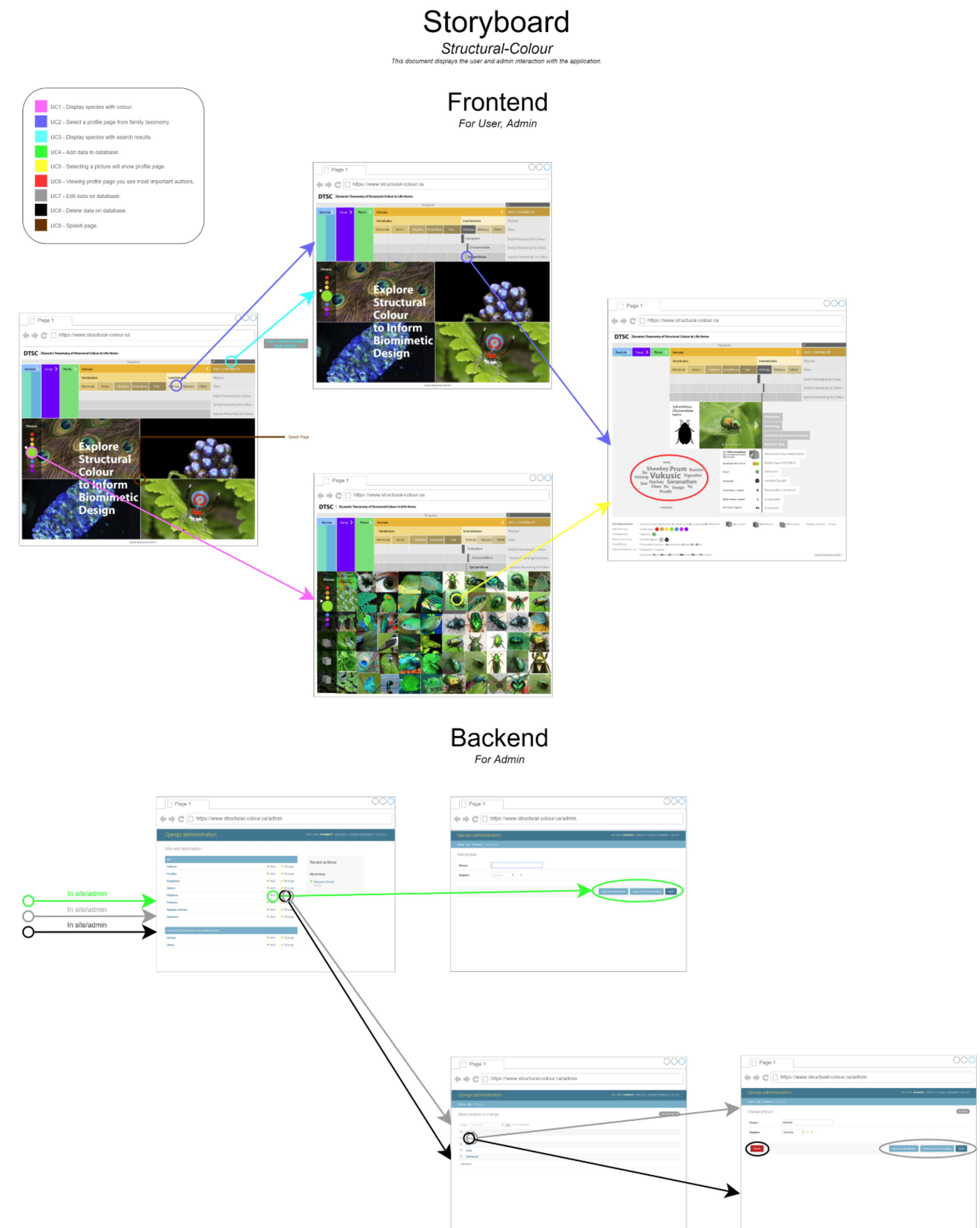




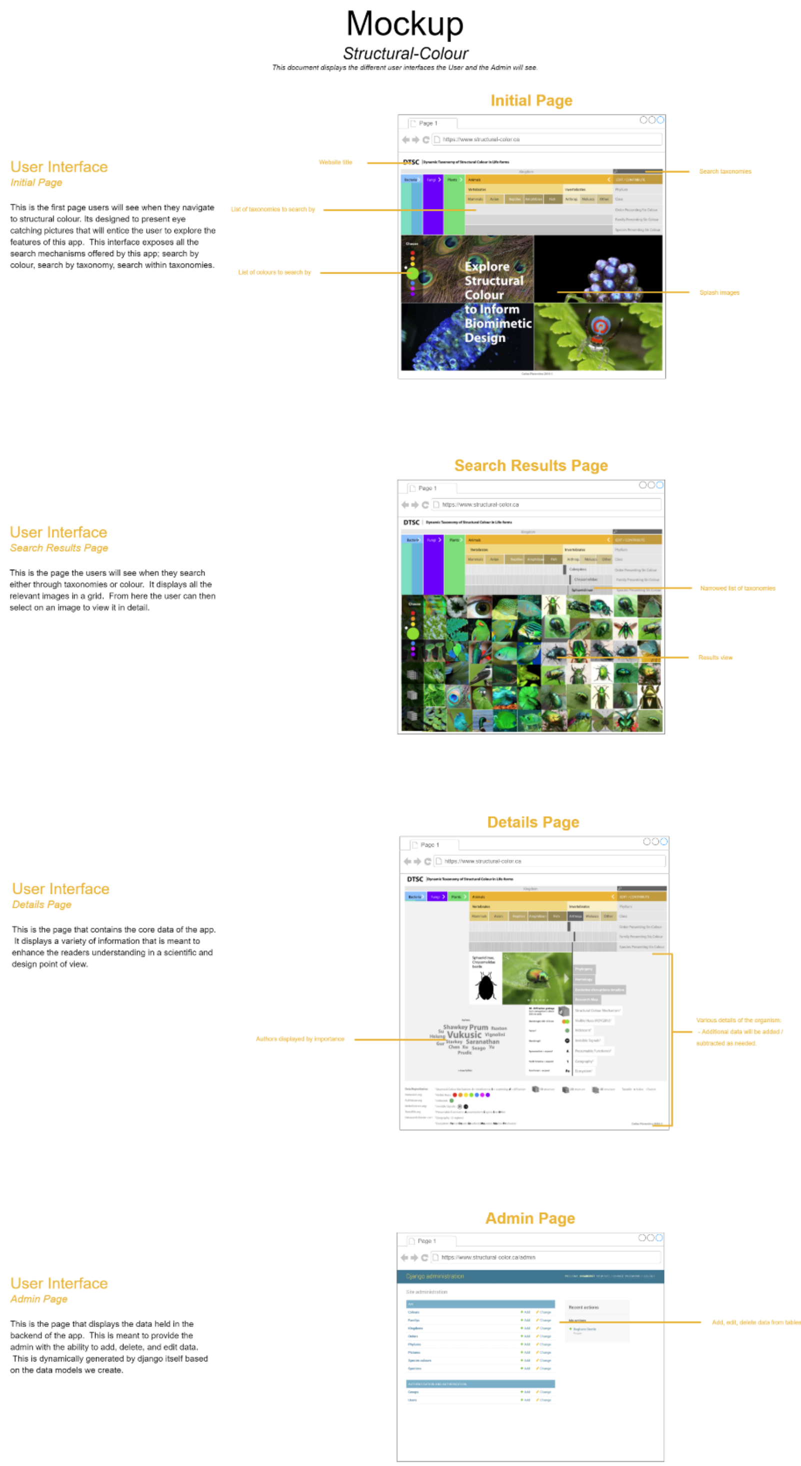




Diagrams for the planning of DTSC (later StrC) site architecture created by CMPUT401 students.



Storyboard of DTSC system created by CMPUT401 students.



Mockup of DTSC described by CMPUT401 students for client documentation.

StrC A Rich Prospect Taxonomy on Structural Colour

Tentative Programming Schedule Carlos Fiorentino

Proposed period of work:

Fall 2018 : September to December : week 1-16
Winter 2019 : January to May : week 17-20

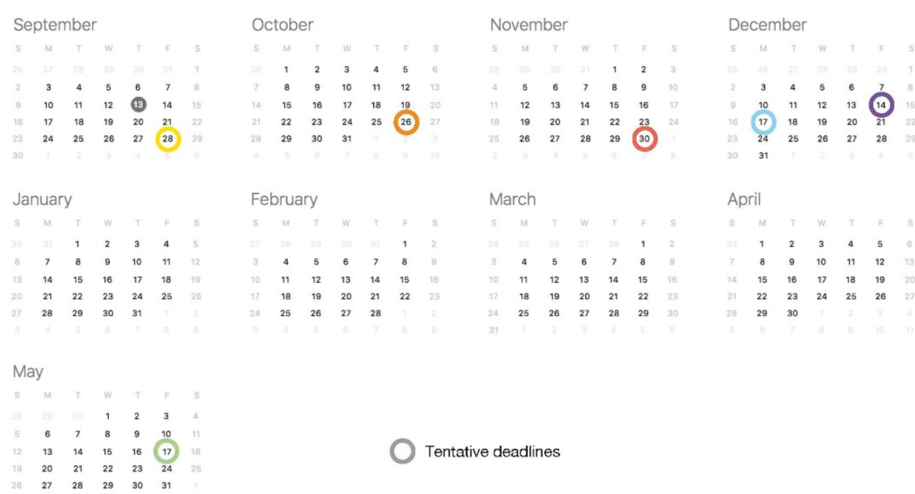
Project tasks [priority in red]

1. Adjustments in texts, colors and layout on main taxonomy and overall site to follow mockup design and guidelines
2. Adjust color of photos in splash page and species
3. Eliminate zoom in-out in main taxonomy
4. Adjust color picker according to mockup design
5. Complete graphics in species page
6. Adjust splash page to mockup design
7. Contributions-feedback Red Layer for species page and ALSO on main taxonomy
8. Backend: Create a mechanism for collecting quantitative data from user interactions and create charts:
   - number of visitors/visits
   - sections activated
   - number of actions done
   - time length of sessions / on sections
   - keywords searched
   - species visited
   - etc.
9. Developing wordcloud, phylogeny, homology and research map widgets (define parameters)
10. Elaborate and develop evolutionary disruptions timeline (content + design tbc)
11. Follow original design for authors details and abstract (see applied in AskNature.org)
12. Integrate 7vortex as a widget: to map researchers, papers, etc.

Project milestones by week

- Weeks 1-4. Setting up new server/domain, restoring back end, tasks 1, 7, 8
- Weeks 5-8. Tasks 2,3,4,5,6,11 / Testing
- Weeks 9-13. Task 9 (widgets) / / Testing widgets
- Weeks 14-15. Tasks 10 and 12
- Week 16. Pilot
- Weeks 13-36. Technical support to the study / Accessing and collecting data from other repositories for StrC 2.0

Calendar



Project schedule for developers of the second stage of development (StrC).

```
StrC adjustments

Main page:
Update logo (replacement file attached)
Eliminate left margin (align to the left, to the logo)
Consistency in block separations: I estimate 2 pixels between groups and splash images, 1 pixel between items of
the taxo (clusters)
Consistency in alignment of the blocks
Add an 'about', 'contact', and 'StrC study' options above the search field (I'll provide info for these later)
Extend the 1 pixel line under the search field
Activate the magnifying lens icon to function as "enter"

Splash page:
Rotate the slides with no repetitions (every 3 sec disolve effect) -> (demo attached)
Eliminate heading "Explore..." of the splash page
Back to splash page when click on logo

"Icicle" taxa:
Remove labels from taxa in icicle when text does not fit
Hoover labels on taxa items when text does not fit
Make type in all active labels of the icicle one point smaller (similar to "choose" label in the colour picker)
Eliminate scales of grey in order, family and species categories, make greys uniform. Keep the item activated
(hoovering, clicked or searched) in darker grey.
Show hand cursor when item are clickable

Colour picker and photogalleries:
Hoover labels (species names) on photos of gallery
If possible, separate the white dot in the picker of the roygvib column
Make gallery left aligned


>>>>>>>Search keywords: include scientific names of species<<<<<<<
add white option to the backend
fix scalability issues of photo entries done from augustana
When clicking on fillum, class, order or family, all the species under that category should be highlighted as if
hoovered (dark gray)

Icicle:
Hoovering labels on galleries centred to the picture
change "Aves" to "Avian"

Species profile:
Add common name outside at the left of the scientific name (bigger and bolder)
Leave some extra space (1 or 2 pixels) between structural colour mechanism text and the photo of the species on
top
Eliminate question sign after iridescent factor
Replace serif font by sansserif bold in iridescent, invisible..., presumable..., geography, ecosystem options
Add legends at the bottom of the page; use the image from the mock up if simplifies the task. The data repository
list will grow, so perhaps make this part editable and collapsable; at least two logos linking to websites will
be placed under this list.*
Letters "I" "S" and "d" added on top or next to the mechanism icons, or special images for them.
Wordcloud and access to authors function.
* Linkeable items under "Data Repositories:"
AskNature logo linked to structural color (https://asknature.org/?s=strucutral+color#.W-cDhi0ZNE4)
7Vortex logo linked to StrC (https://www.7vortex.com/ecosystems/87ce8746-abc3-4b44-87ae-d9612ada7fb0/view)
Barcode of Life Data System (Boldsystems.org)
iNaturalist.org
Webofscience.org
Treeoflife.org
Interagency Taxonomic Information System (ITIS.gov)
Encyclopedia of Life (EOL.org)
V-TEC SCD Structural Color Database (http://iridescent.life)
EDIT Platform for Cybertaxonomy (cybertaxonomy.eu)
Strickland Museum (entomology.museums.ualberta.ca/index.html)
NHM Natural History Museum (http://www.nhm.ac.uk/our-science/collections/entomology-collections.html)
Project Plumage (https://www.zooniverse.org/projects/ghthomas/project-plumage)
PeTaL-The Periodic Table of Life (https://www.grc.nasa.gov/vine/about/what-is-petal/)

Make titles of common names work in two lines when they are too long (see the case of "
Menelaus Blue Morpho")
Bolder typeface for authors in the wordcloud



Bolder typeface for authors in the wordcloud
Replace "N" by a question mark "?" when information is not available
Align legend to the left border of the scientific name
Align labels 1D, 2D and 3D structure horizontally to the cube icons
Add numbers and names of the 5 regions under Geography
Leave 10 pixels of left margin for the data repositories list
Move the title "Data Repositories" under the logos
Can we make the list of data repostories an expandable-collapsable list to occupy only one line?
Adjust the size of AskNature and iNaturalist logos to 7Vortex size
Make the backgound of both logos white
Make linked sites open in a new window
I noticed a glitch in Safari, when switching between species, the silhouette illustration remains if the next
species clicked has no illustration...

WORDCLOUD: VISUALIZE ALL NAMES FROM THE DB, HIGHLIGHT THE AUTHORS LINKED TO SPECIES SELECTED?

ADD ONE LINE OF VERY SMALL TEXT CREDITING THE IMAGE, DOWN LEFT SIDE ALIGNED TO RIGHT
AND A FIELD TEXT IN THE "ADD PICTURE" IN THE BACKEND

MOVE RED+BOX TO THE CENTER OF THE WORDCLOUD

--------------

WIDGETS:

ADD "RED+" BOXES ON TOP OF ALL THE WIDGETS
REDUCE SIZE OF WIDGETS 10-20% (OR USE THE COLOUR PICKER AS A REFERENCE); ALIGN THEM TO THE LEFT
CAN WE MAKE THE PDFS ICONS CLICKABLE TO THE ARTICLES?
IS IS POSSIBLE TO ADD A SOFTER TRANSITION EFFECT WHEN WIDGETS ARE ACTIVATED?

-----------


Feedback red layer:
Add floating label when hoover the +squares: "add comments and suggestions"
Commnet/Contribution window: make all the lines same value as the contact email box
Align left border of the button, and the boxes to the comments text box
Make the label "SUBMIT" bolder

One addition to the feedback red layer: add a red +box on top of the wordcloud of authors; this may require one
more item in the Api "Change feedback"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In species pages: WHEN MECHANISM IS NOT SPECIFIED CHANGE "UNKNOWN - DIFFRACTION GRATTINGS" TO "NOT SPECIFIED"
Add a thin gray outline to the "white circles" under visible hues
CROP THUMBNAILS CENTERING PHOTOS

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Make IP exeptions and purge Google analytics
SEARCH: Scientific species names
SEARCH: how to get keywords typed as stats from analytics
Set Google analytics to track widgets as "event hits"

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AUTHORS WODCLOUD: Names clickable to show a summary list of articles written by individual authors
Articles: assign entire orders

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Make categories (Phyllum, class, order, etc) clickable to select all species in the collection and show the
thumbnails

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MAKE THE RESEARCH MAP SMALLER AND THE BUBBLES BIGGER


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Next:
```
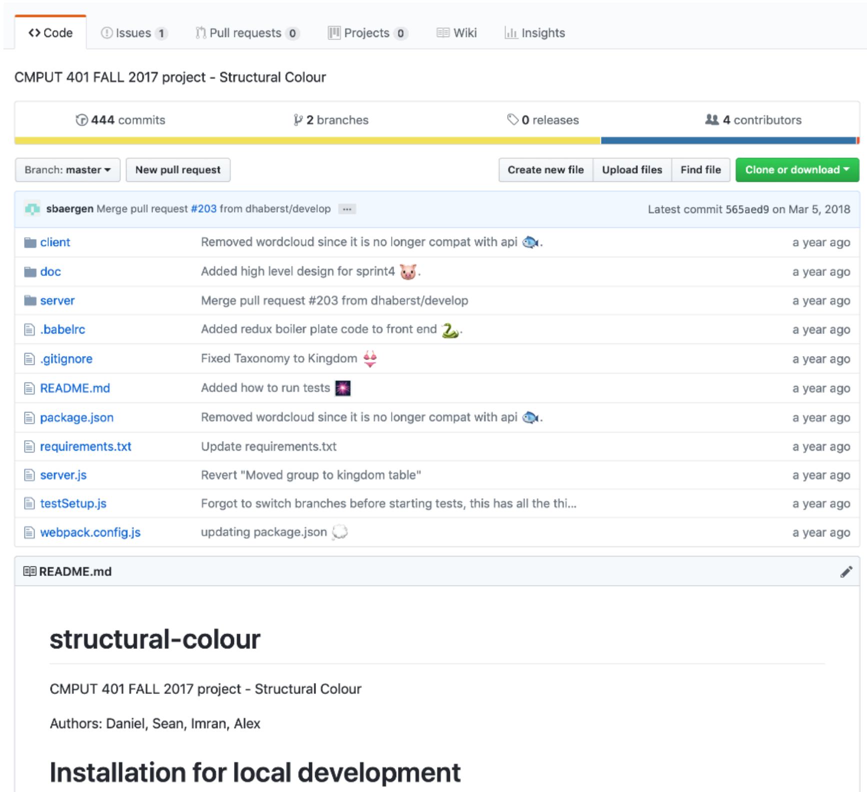
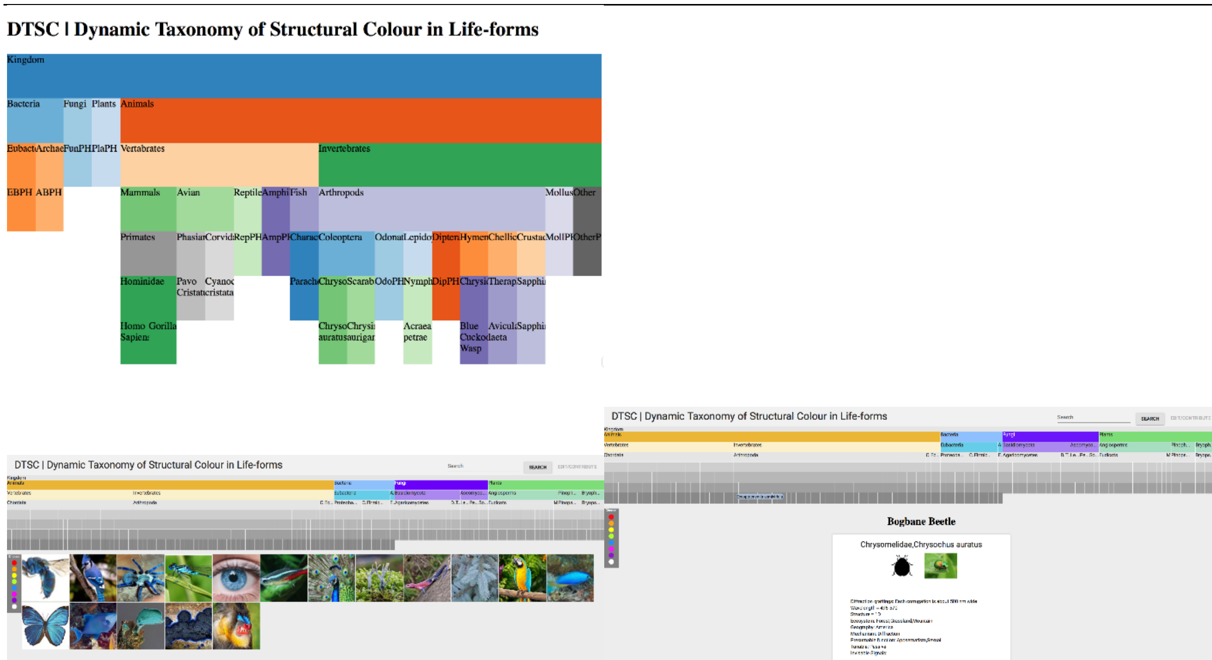

Iteration log; adjustments discussed/required to developers.

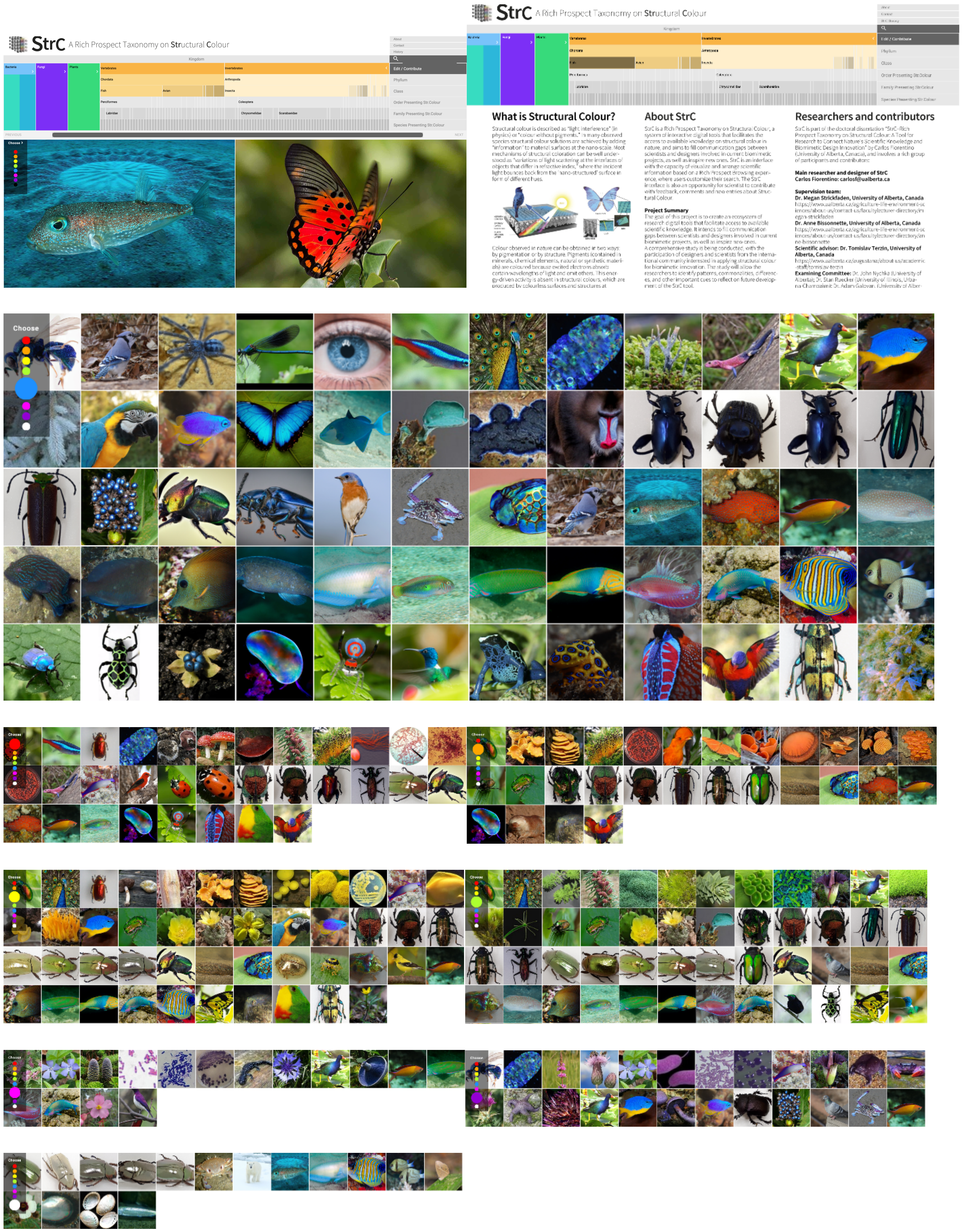


Screenshot of GitHub page; project log from CMPUT401 developer students.

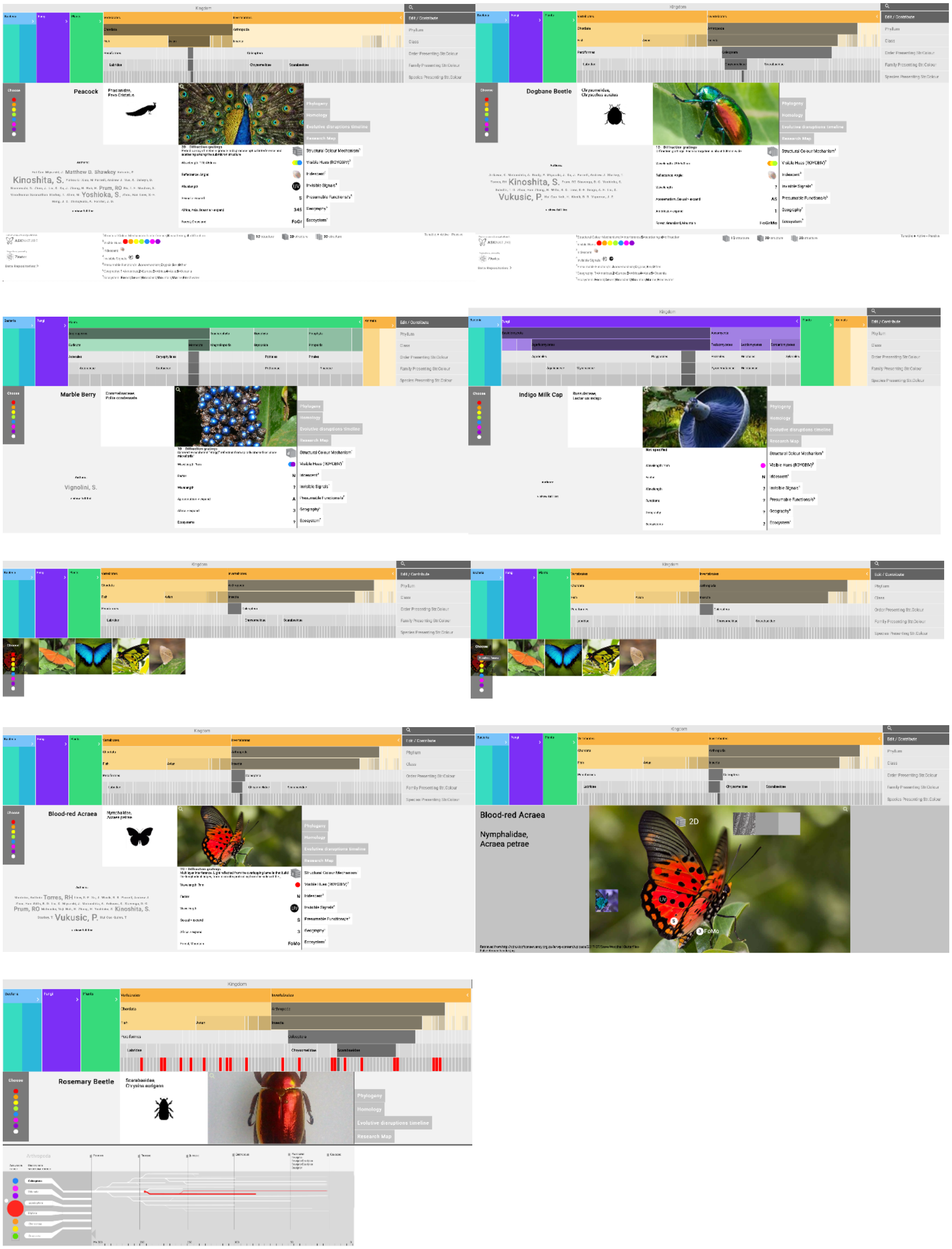
7.2.7 StrC Prototype, Basic Components, and Database Development (Screenshots)



Initial and final screenshots from taxonomy interface developed by CMPUT 401 students.



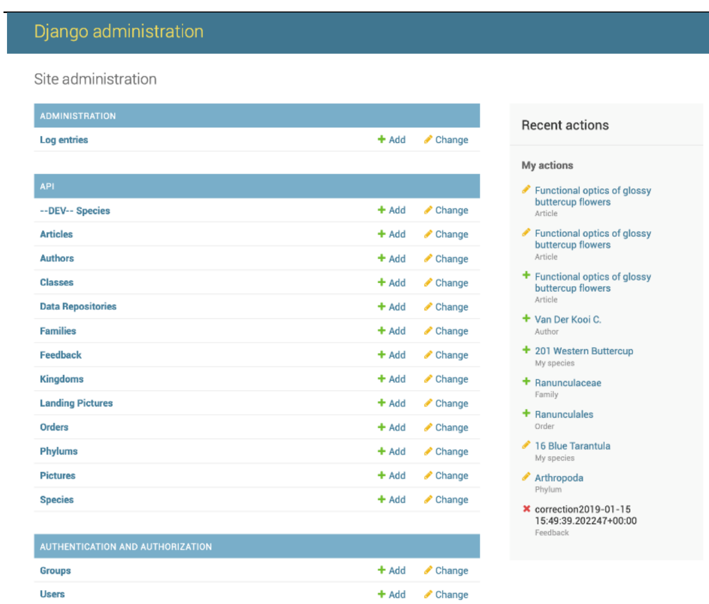
Screenshots of the StrC interface final version.



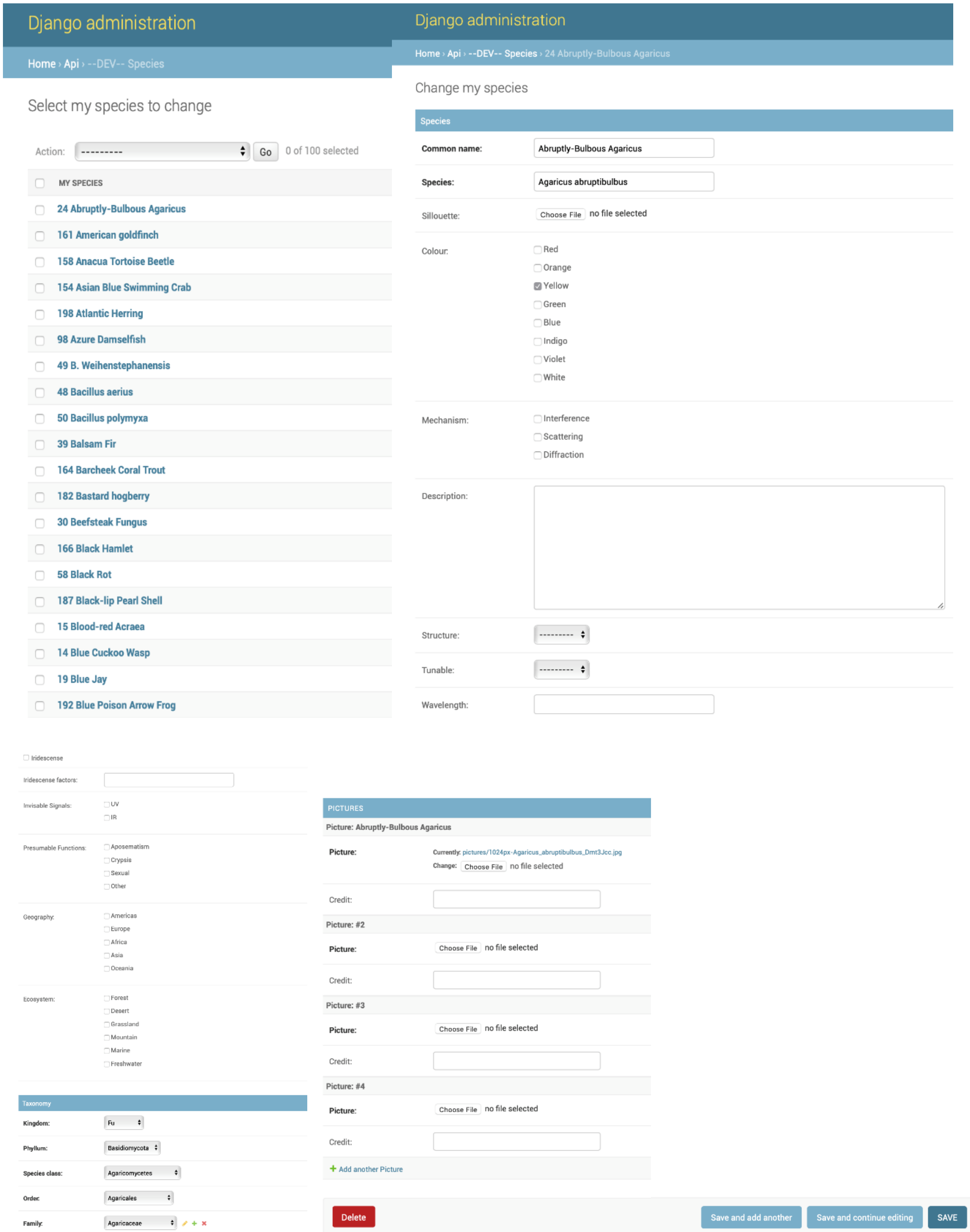
Screenshots of the StrC interface final version.

Screenshots of the StrC interface final version.

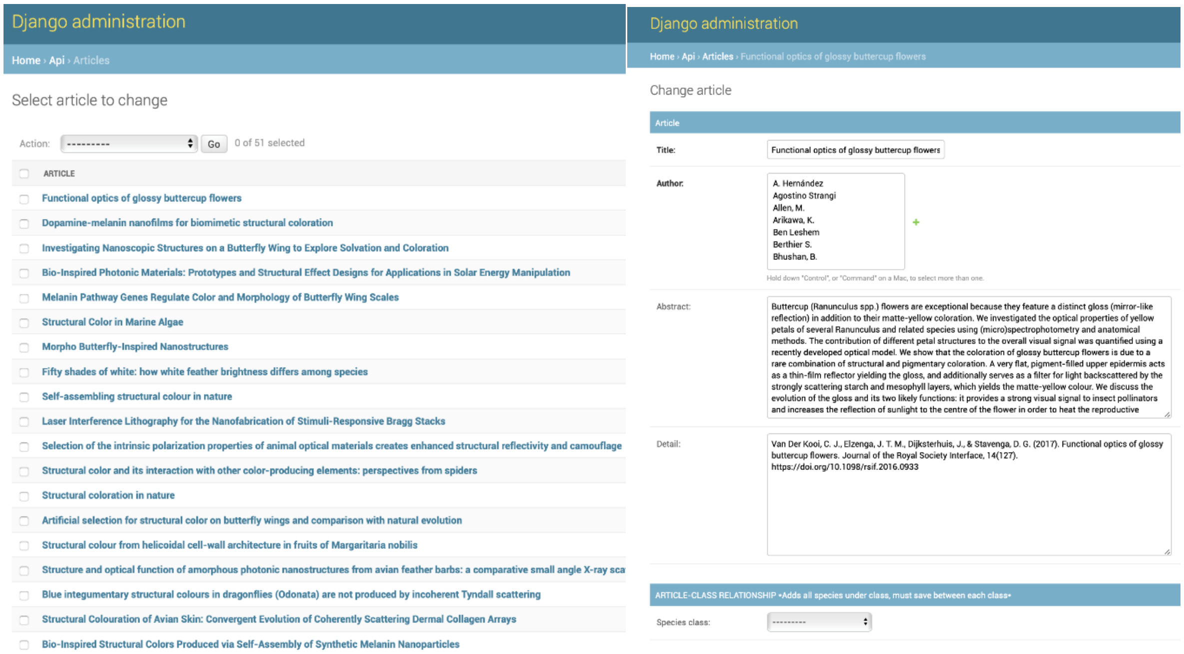
7.2.8 Django API Backend Interface



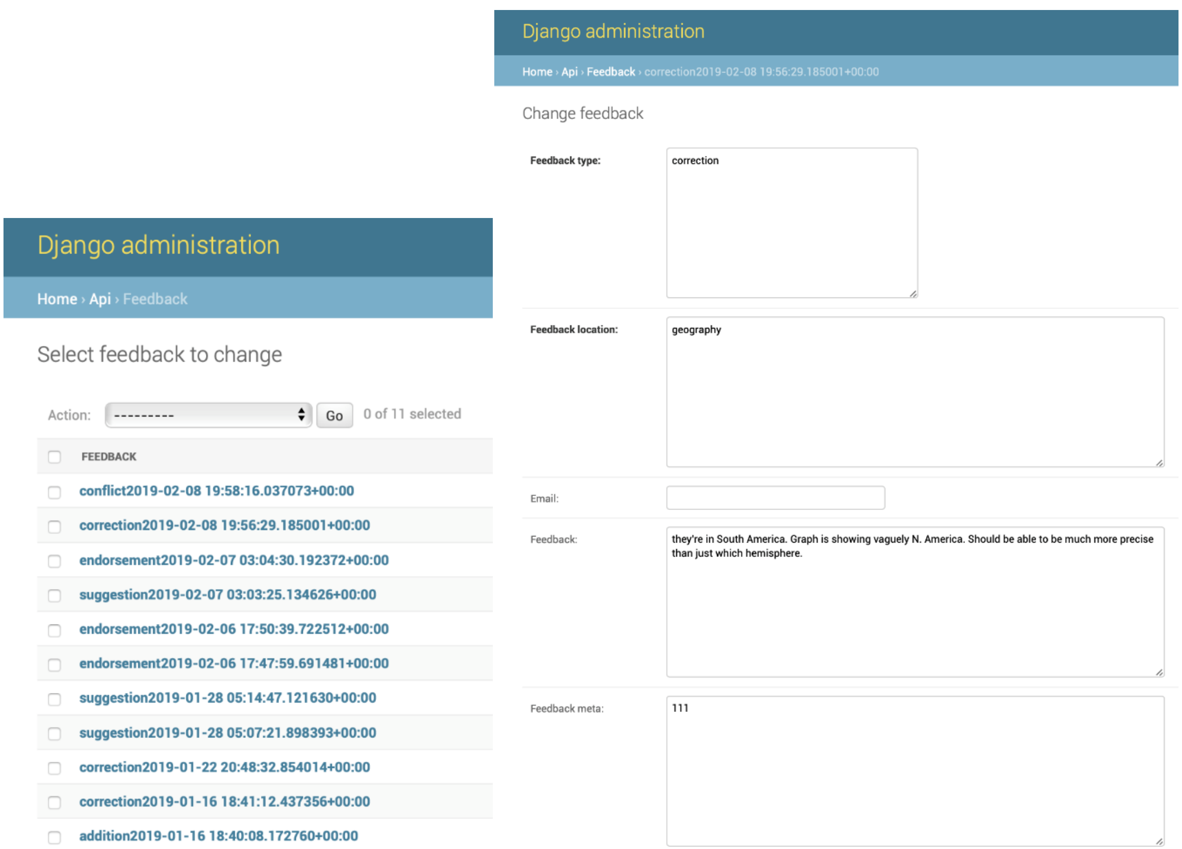
Screenshot of the API administration homepage.



Screenshots of the API administration for items and categories of the collection.

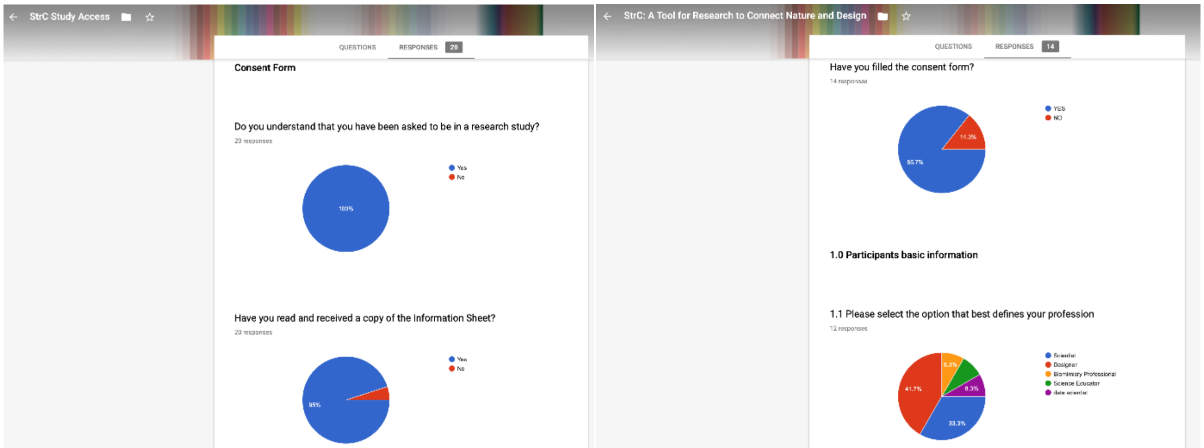


Screenshots of the API administration for literature.

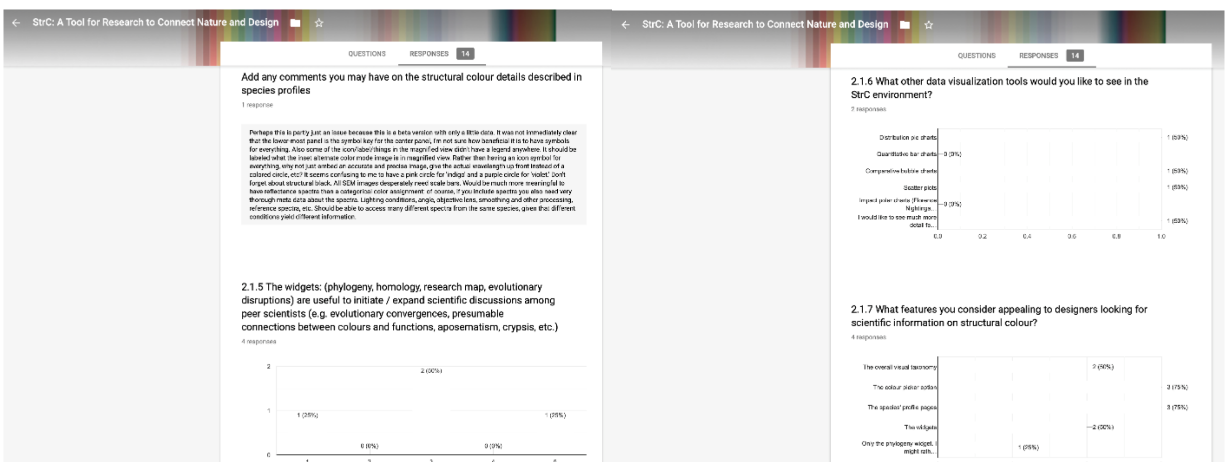


Screenshots of the API collected feedback entries from the "red layer."

7.2.9 Study Access and Survey Administration Backend (Screenshots)

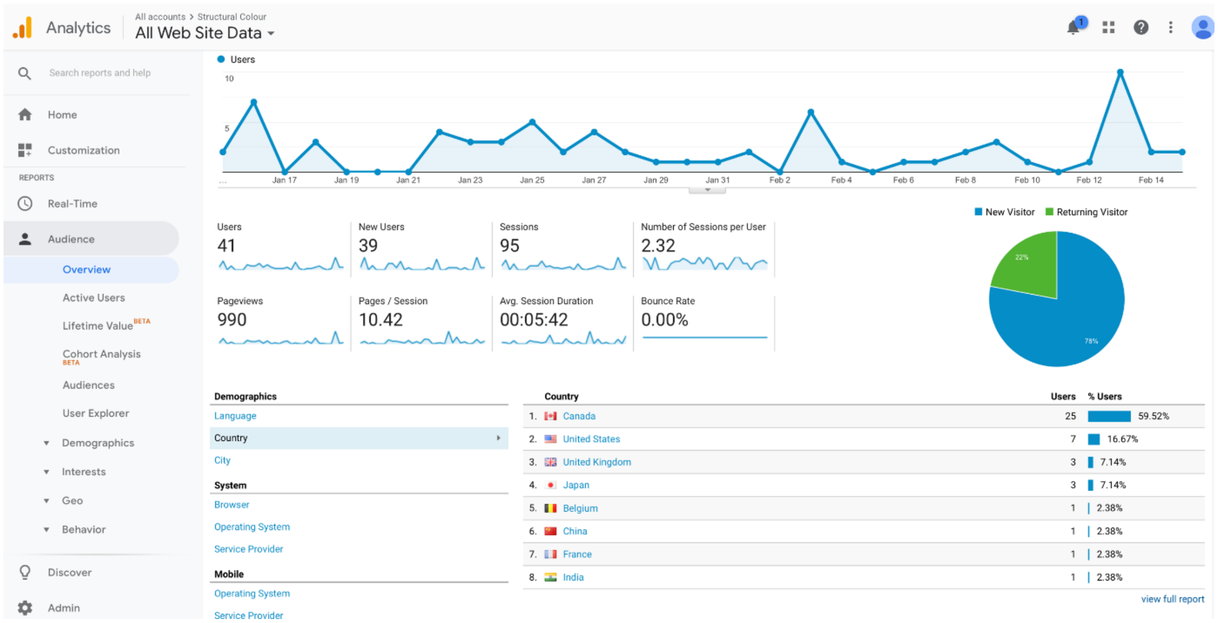


Screenshots of Google Forms administration backend for Study Access and Survey.

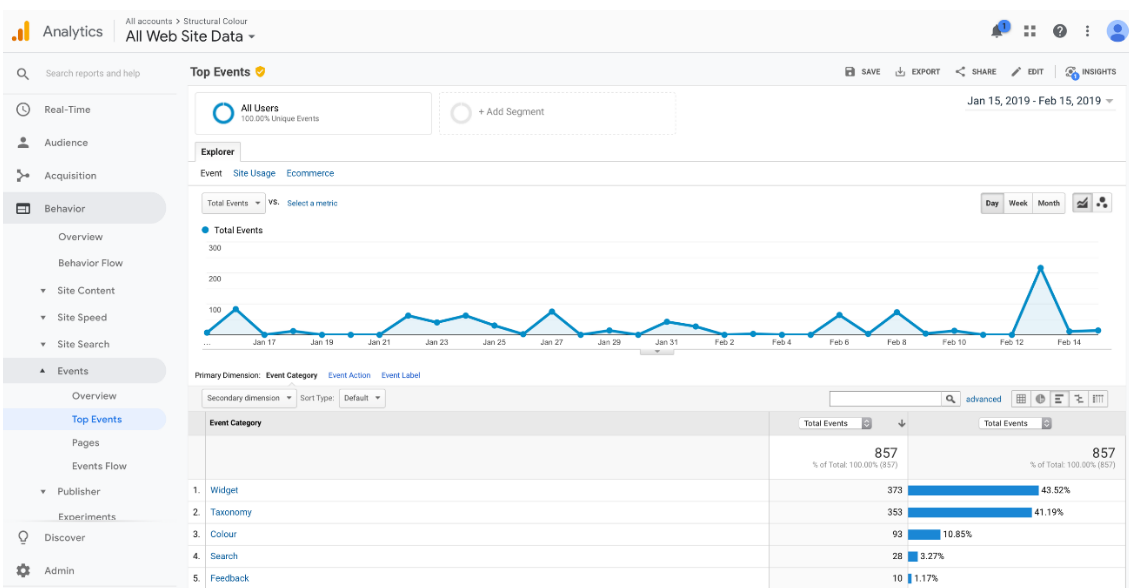


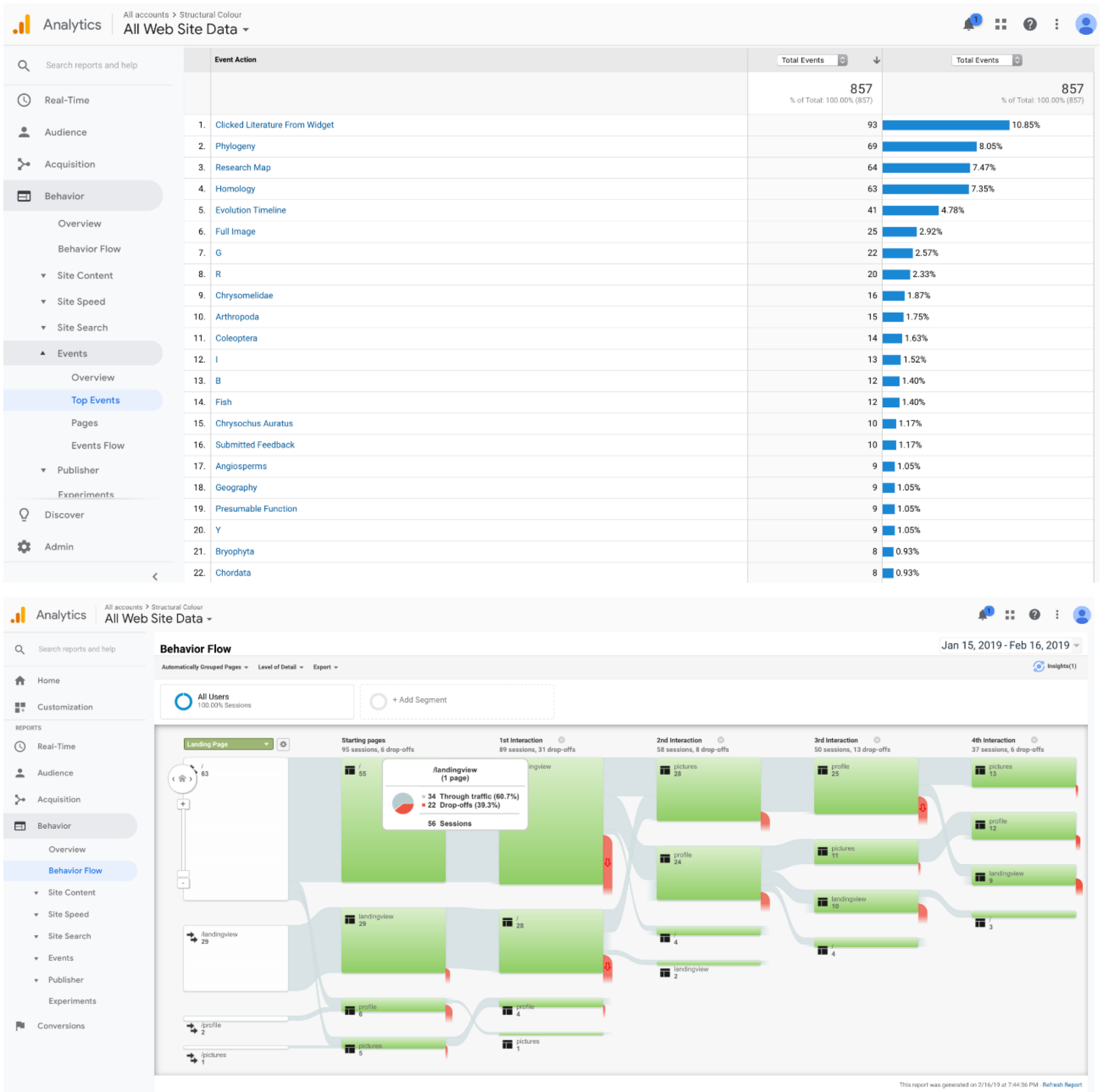
Screenshots of Google Forms administration backend, Survey results.

7.2.10 Google Analytics Backend Interface



Screenshots of Google Analytics backend, overview of StrC interface activity.





Screenshots of Google Analytics backend, summary of StrC category and item events, and behavior flow features.