BIOMIMICRY IN INDUSTRY:
THE PHILOSOPHICAL AND EMPIRICAL RATIONALE FOR REIMAGINING R&D

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BIOMIMICRY IN INDUSTRY:

THE PHILOSOPHICAL AND EMPIRICAL RATIONALE FOR REIMAGINING R&D

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Dissertation

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ABSTRACT

Biomimicry is innovation through emulation of biological forms, processes, patterns, and systems. What motivates practice is a basic understanding of natural selection as a process that favors high-performance, resource-efficient survival strategies – strategies that can be abstracted to address technical challenges from the molecular to systemic scale. Biomimicry has generated commercial solutions in diverse sectors, but industry practice is limited by a lack of clarity around quantitative / qualitative benefits and best practices. This body of work starts to unveil the different dimensions of value biomimicry can offer business, providing evidence of its potential to enhance creativity, increase rates of intellectual property generation, and inform environmentally sustainable solutions. It also details an iterative five-phase biomimicry process, validated in a corporate context, that can serve as a template for industry implementation. Perhaps most importantly, it describes how biomimicry helps us recall a fundamental truth we managed to forget: humans are a part of rather than apart from nature. Innovating from this point of view, we brighten prospects of a flourishing life on this planet.
DEDICATION

This dissertation is dedicated to my late grandmothers and enduring role models, Emily Kennedy and Barbara Rissberger, after whom I am named.
ACKNOWLEDGEMENTS

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CHAPTER I
INTRODUCTION

Summary

Biomimicry is innovation through emulation of biological forms, processes, patterns, and systems (Benyus, 2013). The approach has led to innovations in materials science (e.g. shark-inspired bacterial growth inhibition [Mann et al., 2014] – sharklet.com; desert-beetle inspired advanced surface wettability / liquid management [Zhai et al., 2006] – nbdnano.com), chemistry (e.g. spikemoss-inspired thermo-stabilization [Drew, 2008] - stabilitech.com; mussel-inspired adhesives [Jang, Huang, & Li, 2011] - purebondplywood.com), engineering (e.g. kingfisher-inspired 500 Series Shinkansen Bullet Train (Benyus, 2009); shellfish-inspired mechanical joining system - joinlox.com), waste management (e.g. forest floor-inspired non-directional carpet tiles [Biomimicry 3.8, 2013b; Interface, Inc., 2016]) information technology (e.g. social insect-inspired energy management [Kerbel, Hoeller, & McKeag, 2012] - encycle.com), and organizational design (e.g. fungal network-inspired organizational structure (Walker, 2010). Drawing on estimates of biomimicry’s penetration in various industries, the Fermanian Business & Economic Institute predicts that by 2030, biomimicry could account for $425 billion in US GDP and $1.6 trillion in global GDP, in addition to savings associated with reduced resource depletion and pollution (Fermanian Business &
Economic Institute, 2013). Despite biomimicry’s ability to deliver radical, 
environmentally sustainable product, service, and systems innovations (Lurie-Luke, 
2014; Goel et al., 2015), practice remains limited among business professionals. Like 
others, I maintain that this is in part due to a lack of philosophical and empirical studies 
that specify benefits and offer process insights (Nagel & Stone, 2012; Vincent, 
Bogatyreva, Bogatyrev, Bowyer, & Pahl, 2006), to enhance value perception and ease 
implementation. Little has been published on best practices in biomimicry apart from a 
handful of studies carried out with students (Goel et al., 2015; Goel, Vattam, Wiltgen, & 
Helms, 2012; Wilson, Rosen, Nelson, & Yen, 2010; Yen, Helms, Vattam, & Goel, 2010). 
Results of these studies, conducted in academic settings, may not generalize to industry 
(Bello, Leung, Radebaugh, Tung, & van Witteloostuijn, 2009; Sears, 1986). R&D 
managers will be more compelled to pilot biomimicry within their organizations if they 
can justify the decision and source validated techniques from industry-based field 
studies. To bridge this gap in the literature, I set out to study biomimicry in industry for 
my doctoral dissertation.

The title of my dissertation is “Biomimicry in Industry: The Philosophical and 
Empirical Rationale for Reimagining R&D.” Chapters II and III make philosophical 
arguments for widespread adoption of biomimicry. Chapters IV-VI are empirical 
investigations of the qualitative / quantitative benefits of biomimicry in industry, and 
include procedural recommendations. A five-year industrial assistantship with GOJO 
Industries enabled these field studies. Chapters VII and VIII – explorations of the shock-
absorbing properties of hedgehog spines – were motivated by Chapters II-VI learnings.
Fundamental research on hedgehog spines has generated intellectual property and led to the formation of a biomimicry startup, Hedgemon, LLC.

Philosophical Contributions

Chapter II undercuts common criticisms of biomimicry; specifically, that the approach 1) diminishes the role of the human designer; 2) relies on suboptimal models due to evolutionary incrementalism; 3) demands humans repress their impulse to build; and 4) depletes architecture of human meaning. This chapter reveals how each of these criticisms is based on a shaky philosophical foundation.

Chapter III introduces scholars, students, and professionals in all fields of design to biomimicry and its potential to yield sustainable outcomes. It constructs an argument for deep, thoughtful practice of biomimicry, which considers emulation at all levels: form, process, and ecosystem.

Empirical Contributions

Chapter IV is a GOJO biomimicry case study. GOJO implemented the approach for innovation of energy-efficient liquid soap and sanitizer dispensers. Compared to a historical new product development project with a similar objective and scope, the biomimicry driven project produced double the intellectual property and at least double the energy savings for just one-sixth the resource commitment. Biomimicry also showed potential to increase the overall speed of front end innovation. Chapter IV provided the basis for several hypotheses tested in Chapters V and VI.
In Chapter V we test whether a prototypical set of four narrowed frames of inquiry help R&D professionals identify a greater quantity and variety of biological models, a critical step in the biomimicry process. Frames of inquiry did not have a significant positive effect on biological model identification, but this may have been because high variance among groups within treatments gave our tests low power. This study thus demonstrates that the industrial research context may require larger sample sizes and/or conditions which maximize potential effect sizes to ensure results are discernable. These insights can contribute to how scholars and practitioners continue to pursue best practices for biomimicry in contexts other than the classroom.

In Chapter VI we test the effect of far-field industrial (i.e. man-made) vs. biological analogies on creativity of business professionals from two organizations engaged in the idea generation phase of new product development. Results suggest presenting new product development professionals with biological analogies as ideation stimulus increases novelty and may increase elegance of solutions generated.

Applied Learnings

Chapters II-VI comprise a compelling body of evidence for biomimicry in industry. Emulation of biological forms, processes, patterns, and systems can yield disruptive innovations with real commercial viability. Motivated by these findings, we devised a research program to pursue our own commercial application of biomimicry – hedgehog-inspired impact protection technology. In the wild, hedgehogs climb trees while foraging insects and regularly fall or jump to escape avian predators (Matthews,
1989). They hit the ground at high velocity but walk away uninjured because the quills projecting from their pelts have evolved to absorb shock (Vincent & Owers, 1986).

Chapters VII and VIII are fundamental research studies on the shock absorbing properties of hedgehog spines. These studies, and others, led to innovation of a patent-pending, hedgehog-inspired shock absorbing liner (Kennedy, Fecheyr-Lippens, Hsiung, Paige, & Swift, n.d.) and formation of startup Hedgemon, LLC to commercialize the technology. Initial focus is development of an integral safety component for football helmets to reduce risk of concussion. To date, Hedgemon has raised more than $70K to support ongoing R&D and business development, further solidifying biomimicry’s value.
CHAPTER II

BIOMIMETIC BUILDINGS: THE EMERGING FUTURE OF ARCHITECTURE

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Abstract

Biomimicry is sustainable innovation inspired by Earth’s diverse lifeforms which, thanks to billions of years of evolutionary refinement, embody high-performance, resource-efficient design solutions. Dismissing large potential ecological and economic returns associated with biomimicry, critics argue the approach 1) diminishes the role of the human designer; 2) relies on suboptimal models due to evolutionary incrementalism; 3) demands humans repress their impulse to build; and 4) depletes architecture of human meaning. The purpose of this article is to defend the merits of biomimicry by revealing how poorly founded these assertions are. Each is based on an outdated paradigm that we must shed in order to nurture a new era of architecture.
Introduction

The ancient Greek philosopher, Aristotle, said ‘man, when perfected, is the best of animals’ (Aristotle, Pol. 1.1253a). This laid the foundation for the ‘Great Chain of Being’ [Figure 2.1], a medieval cultural conception which alleges a linear ranking of life forms from lowest, simplest, and least like humans, up through humans, considered the best, most complex, and most intelligent (Marks, 2008).

![Figure 2.1. The Great Chain of Being. Illustration by Laura Kennedy. Reproduced with permission.](image)

The ‘Great Chain of Being’ reflected the dominant Western interpretation of natural order until the eighteenth century, when Carl Linnaeus, a Swedish botanist-physician, introduced a disruptive biological classification system based on a nested, rather than linear hierarchy, with life forms grouped according to similar features. Linnaeus recognized three ‘kingdoms’ of equal rank – animals, plants, and minerals. Within each kingdom were classes; within each class, orders; within each order, genera; and within each genus, species (Marks, 2008). Humans were situated in the animal
kingdom, mammal class, primate order, and in the same genus as apes (Corbey, 2005).

Charles Darwin took another damaging swing at the ‘Great Chain of Being’ with his theory of evolution. In his books *On the Origin of Species by Means of Natural Selection*, published in 1859, and *The Descent of Man, and Selection in Relation to Sex*, published in 1871, Darwin provided robust scientific evidence that humans evolved from an apelike ancestor. Scientific advances spearheaded by Linnaeus and Darwin, repositioned the human as but one twig on an evolutionary tree; a modest figure in an expansive natural history. However, the ghost of the ‘Great Chain of Being’ continues to haunt Western culture. It has proven difficult to relinquish the longstanding belief that humans are superior in value, capacity, and worth relative to other species; a belief that permits us to ravage our environment without concern for the consequences.

Biomimicry – from bios, meaning life, and mimesis, meaning to imitate – is a sustainable design philosophy that jettisons the ‘Great Chain of Being’ in favor of a modern interpretation of humans as a young species among an astounding 30 to 100 million. Since life first emerged on our planet 3.8 billion years ago, biological systems have been evolving high performance, resource-efficient strategies that can be translated to address many of the technical challenges designers face (Benyus, 2008). The term “biomimetics” was coined by Otto Schmitt in the 1960s (Harkness, 2002) and popularized by Janine Benyus and her critically acclaimed 1997 book, *Biomimicry: Innovation Inspired by Nature* (Benyus, 2008). Deep practice of biomimicry requires a fundamentally different perspective of the relationship between humankind, the built
environment, and the rest of nature than what was endorsed by the ‘Great Chain of Being.’

Biomimicry has inspired innovation in diverse fields and is projected to account for $1.6 trillion global output, as well as $0.5 trillion savings associated with reduced resource depletion and pollution, by 2030 (Fermanian Business & Economic Institute, 2013). It has had a particularly significant impact in the architectural field, where it has led to innovations in climate control, ventilation, and structural integrity, among other features. Melbourne’s Council House 2 was inspired by gas and heat exchange in termite mounds [Figure 2.2]; and London’s 30 St. Mary Axe building, affectionately called ‘The Gherkin,’ by structural reinforcement in sea sponges [Figure 2.3]. For many centuries, we were blind to the possibility that animals and plants, seen as lower life forms, had anything to teach us, but these examples show how much we have to learn.

Figure 2.2. Melbourne’s Council House 2 (Left, Photo by Nick Carson, CC BY-SA 3.0) inspired by termite mounds (Right, Photo by Brewbooks / Flickr, CC BY-SA 2.0).

Figure 2.3. London’s 30 St. Mary Axe building (Left, Photo by Aurelien Guichard, CC BY-SA 2.0) inspired by sea sponges (Right, public domain).
The building sector offers more opportunities for cost-effective greenhouse gas mitigation than any other (Metz, Davidson, Bosch, Dave, & Meyer, 2007) and biomimicry case studies demonstrate the approach’s ability to guide eco-integration. As such, architects are uniquely positioned to embrace biomimicry and become leaders of a sustainability transition. Biomimicry has proven ecologically and economically viable in the face of critics who cling to an antiquated view of humans as the champion life form. Criticisms leveled against biomimicry as an approach to design include: 1) biomimicry diminishes the role of the human designer, 2) design inspired by biological models is too tightly bound by evolutionary incrementalism; and 3) eco-conscious approaches like biomimicry urge humans to repress their impulse to build. Some critics even go so far as to argue that 4) biomimetic architecture reflects an impoverishment of human meaning (Kaplinsky, 2006). In this article, I defend the merits of biomimicry by revealing how poorly founded these assertions are. Each is based on an outdated paradigm, which ‘must be destroyed in order to build new knowledge of a type that is more socially robust, more scientifically reliable, stable, and above all able to better express our needs, values, and dreams’ (Gebeshuber, Gruber, & Drack, 2009). We have to create space, especially in the architectural world, for approaches such as biomimicry, which provides an environmentally ethical framework for architectural design, urban planning, and economic development in general.
In Defense of Biomimicry

*Bio*mimicry encourages humility, not diminished self-confidence

The biomimicry philosophy encourages humility in the face of our natural limits. Humans are not a rank above other species with regard to eco-dependencies. We cannot absolve ourselves of our reliance on nature. However, humility is not self-deprecating. A humble person is honest about who he is and does not act as if he is more (Cloud, 2006); he is not arrogant, but this does not mean he cannot be self-assured. Humans can step down from the pedestal once provided by the ‘Great Chain of Being’ and still stand tall. In fact, humility can be a source of confidence. In biomimicry, humility is seen as a ‘source of power, a focusing mechanism’ (Benyus, 2008). If we admit that all problems are not solvable by our own genius, we are empowered to look for alternative solutions (Orr, 1995).

Architect William McDonough is an example of a humble yet confident biomimicry practitioner. McDonough has accepted that the continued prosperity of humankind is dependent on the health of the biosphere (Braungart & McDonough, 2008; McDonough, 2005). McDonough rejects the traditional ‘cradle-to-grave’ manufacturing model, in which up to 90 percent of materials used in production are cast off as industrial waste. Instead, McDonough advocates a ‘cradle-to-cradle’ model. ‘Cradle-to-cradle’ manufacture emulates nature’s closed loop use of materials (McDonough, 2005). In nature, an organism’s waste is cycled through the ecosystem and becomes nutrient for other living things. In ‘cradle-to-cradle’ manufacture, waste
from one production line becomes feedstock for another. Products at the end of their lifecycle safely re-enter the environment and decompose into biological nutrient, or are disassembled into ‘technical nutrient’ and up-cycled – which means they are recycled to form higher-grade product (Braungart & McDonough, 2008) [Figure 2.4]. McDonough has designed ‘cradle-to-cradle’ cities for the Chinese government that could house more than a hundred million people. His blueprints are respectful of each site’s hydrology, biota, wind, and solar income. In each city all sewage is up-cycled, water waste is converted into natural gas via constructive wetlands, and solid waste is used as farming compost (McDonough, 2005).

Figure 2.4. Diagram of biological and technical nutrient cycles in William McDonough’s ‘cradle-to-cradle’ model. Illustration by Zhying.lim / Wikimedia Commons. Reproduced under CC BY-SA 3.0.

Biomimicry does not encourage diminished self-confidence

In fact, biomimicry places great faith in a designer’s creative capacity, which allows him to apply biological insights in a manner suited to human application. The
measure of a good idea cannot be found in nature alone, but only in how the human adapts it to his ends. Mercedes-Benz engineers turned to nature for advice in their quest to design a car with ample interior space, high stability, high maneuverability, and low drag. When the boxfish (*Ostracion meleagris*) emerged as a potential natural model, the engineers were not deterred by its bulky, counterintuitive appearance; they remained open-minded, and were able to translate the boxfish form into an aerodynamic concept car, boasting 20 percent less fuel consumption compared to similar-sized models (Bartol, Goron, Webb, Weihs, & Gharib, 2008) [Figure 2.5].

This process of translation resulted in a design that is not a replica of the organism that inspired it, but utilizes the same functional concepts (Zari, 2010). Humans’ unique ability to bring into mind things that are not present (Robinson, 2014) and formulate strategies (Capra & Luisi, 2016) enables creative abstraction, and abstraction of biological principles is a critical step in biomimicry.
Biomimicry is not constrained by evolutionary incrementalism

Nature’s designs are developed through natural selection, which proceeds incrementally. The evolving anatomy of an organism is constrained by the anatomy and genetic makeup of its evolutionary ancestors. While nature cannot elect to wipe the slate clean and redesign an organism from scratch, the human designer can scrap existing design concepts and choose to start over (Kaplinsky, 2006). The giraffe’s neck might be considered an example of a suboptimal result of nature’s incremental design. ‘No [human] designer would make the nerve connection between the brain and larynx of a giraffe by looping it all the way down the neck and back up to the throat’ (Kaplinsky, 2006). Nature had limited options due to the anatomy of the giraffe ancestor, in which the nerve looped around a blood vessel at the base of the neck (Kaplinsky, 2006).

Nature is not a designer, so the comparison between nature and a designer is a priori false. We may speak of the “design” of a biological system, but in doing so we use metaphorical language. Design requires reflective consciousness, and this ability, as far as we know, is limited to humans and the great apes. As such, there is no design in nature at large, only selective processes that respond to immediate environmental cues (Capra & Luisi, 2016). Instead of comparing human design processes to natural selection, one should consider whether the outcomes of natural selection – thriving biological models – have anything to offer. Biological analogies can stimulate human creativity in new ways, enhancing our own problem-solving ability (Wilson, Rosen, Nelson, & Yen, 2010). Besides, it is a mistake to cast off the design of the giraffe’s neck
as an evolutionary blunder. As the giraffe’s neck elongated, it evolved a unique mechanism for preventing lethally high blood pressure to the head when it bows to drink. The arteries in its neck automatically constrict to prevent blood from pooling with gravitational force. This mechanism inspired the biomimetic ‘G-raffe’ fighter pilot acceleration suit. The fabric of the suit tenses with air pressure, compressing the body in strategic areas to maintain even blood circulation. Wearing this biomimetic suit, a jet pilot can withstand up to nine G force without losing sensory control. Without the suit the average human would lose consciousness at four to five G (Booth, 2012). Giraffe anatomy may be odd, but close study showed its potential for informing human design.

_Biomimicry does not urge humans to repress their impulse to build_

According to Biomimicry 3.8, an organization founded by biomimicry thought leaders Janine Benyus and Dayna Baumeister, the goal of biomimicry is to create more sustainable designs (Benyus 2013). The likelihood of sustainable outcomes increases when practitioners consider the form, process, and ecosystem levels of biomimetic design (Kennedy, Fecheyr-Lippens, Hsiung, Niewiarowski, & Kolodziej, 2015). Those who still correlate low impact design with the extent of untouched nature presume the biomimicry ideal is to not build at all. That is not the case. Biomimicry encourages humans to keep building, but to render construction consistent with life on earth over the long haul (Mathews, 2011). Right now, human production and post-production maintenance often have a negative impact on the environment. For example,
constructing a large dam requires concrete. The production of concrete results in excessive CO2 emissions. Post-production effects of a concrete dam can include soil erosion; species endangerment if dam bypass routes are not constructed for migrating species; spread of disease since water flow decreases and the river turns into a breeding ground for parasites; etc. Nature holds lessons for life-friendly manufacture and maintenance. Consider the fact that the total biomass of ants on earth is greater than the total biomass of humans, yet the ants do not pollute or otherwise degrade their environment (Braungart & McDonough, 2008). A tool called Life’s Principles [Figure 2.6], developed by Biomimicry 3.8, summarizes six major principles and 20 sub-principles embodied by the vast majority of organisms and ecosystems on earth. If we use Life’s Principles as a benchmark for good design, we may achieve the same neutrality possessed by the ants. Our socioeconomic processes will no longer create friction with the ecological processes on which we depend (Mathews, 2011).
Figure 2.6. Life's Principles, a benchmarking tool for biomimetic design that identifies principles embodied by most species on Earth. Its purpose is to help practitioners create designs that fit seamlessly within the larger natural system. Illustration by Biomimicry 3.8. Reproduced under CC BY-NC-ND.

**Biomimetic architecture does not reflect an impoverishment of human meaning**

At least one critic of biomimicry has contended that biomimetic architecture which references animal or plant forms reflects an ‘impoverishment of human meaning’ (Kaplinsky, 2006). Yet humans derive meaning from non-human form. The biophilia
hypothesis suggests all humans have an innate, positive emotional response to architectural form that mimics any naturally occurring geometry (Wilson, 1984). This includes geometries embodied by plants and animals. Many people are enamored by the columns in Gaudi’s Sagrada Família, which mirror branching trees (Armengol, 2001), and the scallop-shaped motifs used extensively in cathedrals (Goss, 1975) [Figure 2.7].

Figure 2.7. Tree-like columns in Gaudi’s Sagrada Família (Left, Photo by Enric / Wikimedia Commons, CC BY-SA 3.0) and a scallop-shaped niche in the façade of the Cathedral of Girona (Right, Photo by Georges Jansoone, CC BY-SA 3.0).

This assertion also presumes biomimetic architecture is exclusively modeled after non-human animals and plants. Humans are biological beings, and biomimicry does not exclude humans from study. TECTONICA Architecture, a Puerto Rican firm, designed reinforced concrete building frames with reduced seismic vulnerability inspired by the human femur’s structural strength. The frame technology, called STICK.S, emulates the human femur’s hollow cylinder design to provide maximum strength with minimum material. STICK.S exhibits 35 percent less base shear under lateral loads, and uses a remarkable 30 percent less material compared to conventional building frames (EHSAAN, 2011) [Figure 2.8].
Figure 2.8. STICK.S building frames inspired by the human femur. Illustrated by Wilfredo Mendez. Reproduced with permission.
Conclusion

Our understanding of humans is transitioning from nature’s best animal, as the ‘Great Chain of Being’ purported for centuries, to one of nature’s youngest animals. If Earth’s history were compressed into one calendar year, beginning one minute past midnight on the 1st of January, life appeared on the 25th of February, and humans on the 31st of December, at 11:49 PM. Civilization has existed for only one minute, and modern industrial society, only two seconds (Milbrath, 1996). Biomimicry is a design ethic that has emerged from this shift in understanding. Biomimetic design emulates biological systems refined over 3.8 billion years of evolution (Benyus, 2008).

Critics of biomimicry cling to a dangerous, dated cultural conception of humans as the ultimate life form. They argue that biomimicry diminishes the role of the human designer. It does not. We can step down from the pedestal once provided by the ‘Great Chain of Being’ and still retain our confidence as designers. The human is of central importance in biomimicry, since the approach depends on the designer’s ability to distill what he learns about biology into a set of abstract design principles which can be implemented to solve a human design problem. Critics also argue that we should not seek Nature’s advice when it comes to design, since Nature designs incrementally. Species are built from a binding template provided by their evolutionary ancestors. This fact does not mean the outcomes of natural selection have nothing to offer us. We can learn from a leaf how to harness energy without creating toxic byproducts; from a diatom, how to effectively absorb mechanical stresses. Critics also assert that
Biomimicry’s mission of sustainability forces humans to repress their impulse to build. This cause-and-effect relationship is unfounded. Biomimicry recognizes that humans, and human developments, are in no way separate from the ecosystems in which they exist. Humans are part of nature. As biotic citizens, our handiwork is as much an expression of nature as is the ‘handiwork of the spider or the bee’ (Mathews, 2011). We should continue to build, but our designs should support rather than stifle life on earth. Finally, some critics contend biomimetic architecture that references animal and plant forms reflects an impoverishment of human meaning (Kaplinsky, 2006). This neglects a large body of evidence suggesting humans have a positive emotional response when their built environment contains naturally occurring geometries of any kind, including those of plants and animals (Wilson, 1984).

Architects who adopt biomimicry as an approach to sustainable building will incite small shifts in thinking with their biomimetic designs, which in turn may lead to striking, positive changes in the broader material world (Meadows, 2009) and in turn our culture. To quote Pedersen Zari, ‘Incorporation of a thorough understanding of biology and ecology in architectural design will be significant in the creation of a built environment that contributes to the health of human communities, while increasing positive integration with natural carbon cycles’ (Zari, 2010).

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CHAPTER III

BIOMIMICRY: A PATH TO SUSTAINABLE INNOVATION

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Introduction

In his 1998 article, “Design for a Sustainable World,” Victor Margolin argues that our ecological plight is beckoning designers to broaden their purpose beyond shaping commodities for clients (Margolin, 1998). Designers are poised to become agents of change that guide a sustainability transition. To do so, they must proactively mold the future profile of their profession by strategically adopting new forms of practice (Findeli, 2001). Biomimicry is an emerging paradigm that can help launch designers into their new role as sustainability interventionists. However, biomimicry does not necessarily render sustainable outcomes. To increase the likelihood of sustainable outcomes, practitioners must consider the form, process, and ecosystem levels of biomimetic design.

The purpose of this paper is to introduce scholars, students, and professionals in all fields of design to biomimicry and to its potential to yield sustainable outcomes when
practiced in a deep, thoughtful way. The design community is an important leverage point for fueling dialogue about biomimicry because designers work “at the nexus of values, attitudes, needs, and actions” and, therefore, are uniquely positioned to act as transdisciplinary integrators and facilitators (Wahl & Baxter, 2008).

What is Biomimicry?

Biomimicry involves learning from and emulating biological forms, processes, and ecosystems tested by the environment and refined through evolution (Benyus, 2013). Biomimicry can be applied to solve technical and social challenges of any scale (Benyus, 2008). Biology has inspired design since prehistoric man fashioned spears from the teeth of animals and mimicked the effective sneak-and-pounce hunting technique of large predators, but the development of a methodological framework for translating biological strategies into design innovations is a recent one. American inventor, Otto Schmitt, coined the term “biomimetics” in the 1960s to describe the transfer of ideas from biology to technology (Harkness, 2002; Schmitt, 1938). Three decades later, biomimicry was popularized by Janine Benyus, who broadcast its enormous potential to inform a new era of design in her critically acclaimed book, Biomimicry: Innovation Inspired by Nature (Benyus, 2008).

Biomimicry is a burgeoning field of study, as evidenced by a growing demand for training in biomimicry theory and practice (Lepora, Verschure, & Prescott, 2013) and a fivefold increase in biomimicry patents, scholarly articles, and research grants since
According to a report by the Fermanian Business & Economic Institute, biomimicry could account for $425 billion of the U.S. gross domestic product (GDP) and $1.6 trillion of global output by 2030 (Fermanian Business & Economic Institute, 2013). The popularization of biomimicry is exciting not just because of its economic prospects, but because of its tremendous potential to inspire eco-friendly designs at this critical juncture in human history. Biomimicry forces a new set of questions that can be applied to the design process, as well as to the outcome. Biological designs are, for instance, resilient, adaptable, multifunctional, regenerative, and generally zero-waste. When deeply informed by biology, design thinking shifts away from an anthropocentric model and considers product life cycles and earth system limitations.

Some scholars argue that the sustainability criterion is too limiting (Rawlings, Bramble, & Staniland, 2012), but “smart companies now treat sustainability as innovation’s new frontier” (Nidumolu, Coimbatore, & Rangaswami, 2009). When tackled appropriately, it offers opportunities for lowering costs and generating additional revenues, and it enables companies to create new businesses to achieve competitive advantage. However, “imitation of the living world is not by default environmentally superior” (Reap, Baumeister, & Bras, 2005). Therefore, informing designers, among others, about the circumstances under which biomimicry is most likely to lead to sustainable solutions is important so that they can engage with the future in a more direct way (Margolin, 2007). At its best, biomimicry is an elegant merger of sustainability and innovation that allows designers to continue earning a living within a system
dominated by a consumer culture, while working alongside biologists to co-create a human civilization able to flourish within the ecological limits of our planetary support system (Margolin, 1998; Wahl & Baxter, 2008).

Biomimetic Design Practice

Biologists are key players in the biomimicry design process because it relies heavily on biological knowledge; however, the role of the designer remains central. This orientation is particularly true when it comes to abstracting biological strategies into more broadly applicable design principles and implementing them to solve human challenges (Benyus, 2013). The aim of biomimicry is not to create an exact replica of a natural form, process, or ecosystem; instead, it is to derive design principles from biology and use those principles as stimulus for ideation. That said, a final biomimetic solution should clearly evidence a transfer of functional or organizational principle from biology. After all, the purpose of biomimicry is to tap the knowledge embodied by nature’s 3.8 billion years of research and development (Benyus, 2008), and accomplishing this goal is not possible if the functional analogy between the natural model and the final design is lost in translation.

Biomimicry and Sustainability: The Direct Connection

Humans are currently using energy and resources unsustainably. Through biomimicry, designers can guide development of technologies that have net zero or net positive environmental consequences because biological solutions have been time-
tested by billions of years of evolution and embody successful strategies for thriving on earth (Benyus, 2013). To demonstrate how biomimicry—repurposing nature’s best ideas to solve human challenges—can help inform sustainable design, consider the following.

TRIZ, a widely-used engineering problem-solving tool, was adapted to create BioTRIZ (Vincent & Mann, 2002). The original TRIZ, developed by Soviet inventor Genrich Altshuller and his colleagues in 1946, is a matrix where intersections represent engineering tradeoffs; for instance, to make a vehicle go faster, you need more power, which consumes more fuel (Domb, 1997). At each intersection, a cell contains numbers that reference technological design principles for resolving a trade-off (Domb, 1997). For example, if the vehicle’s body is made more aerodynamic, you can make the vehicle go faster with the same amount of power and fuel. To create BioTRIZ, researchers analyzed 2,500 trade-offs and resolutions in biology and populated a matrix with biological instead of technological design principles (Sartori, Ujjwal, & Chakrabarti, 2010). Analysts found only a 12% overlap between trade-off resolutions recommended by BioTRIZ vs. TRIZ, which shows that biology solves problems differently than technology. In technology, the manipulation of energy may account for up to 70% of the solution, whereas in biology, energy never figures into more than 5% of the solution. Instead of manipulating energy, biological solutions tend to leverage information transfer and structure (Bogatyrev & Bogatyreva, 2009b; T. McKeag, 2013).

Biomimicry marks a divergence from the unsustainable Industrial Revolution, which was “an era based on what we can extract from nature” (Benyus, 2008). Emulating biology is different from harvesting or domesticating organisms to accomplish
a desired function. This difference might seem obvious; however, newcomers to biomimicry commonly seek

“to use an organism to ‘do what it does’ instead of leveraging the design principles embodied by the organism. This is the equivalent of using fireflies themselves to produce light, rather than understanding and applying the complex chemistry involved in bioluminescence” (Helms, Vattam, & Goel, 2009).

Biomimicry and Sustainability: The Deeper Connection

Beyond the direct connection between biomimicry and sustainability—the simple fact that in emulating biological systems we are emulating strategies time-tested by evolution—a much deeper connection also emerges. Biomimicry does not necessarily render sustainable outcomes, and we cannot overlook this fact (Reap et al., 2005). A biomimetic solution could get high marks in functional performance but fail miserably in a sustainable life cycle analysis (Reap et al., 2005). Thus, designers who want to use biomimicry to create more sustainable designs must strive to emulate biological lessons on three levels: form, process, and ecosystem (Janine M. Benyus, 2013). This multilevel approach is most effective for achieving solutions that inspire awe in terms of sustainable performance:

Form

At the first level, emulating form, consider as an example the giant leaves of the Amazon water lily. The shape and support ribs of the leaves can inform a new innovation of lightweight but structurally strong building panels (Attenborough, 1995). However, this innovation might or might not be sustainable. For example, if these
panels are made of toxic materials that pollute the environment, the costs outweigh the benefits.

Process

At the second level of biomimicry, the focus is on emulating biological processes, or more specifically, how nature manufactures. Nature assembles structures at ambient temperature and pressure using non-toxic chemistry.\(^1\) By contrast, most factories form product by carving, bending, melting, casting, or otherwise manipulating large blocks of raw materials at high temperatures and pressures. Compared to biological manufacturing, the factory approach shows tremendous room for improvement. It is much more energy-intensive, polluting, and wasteful (Faludi, 2005). Encouraging a large-scale shift from traditional to biomimetic manufacturing will be difficult, given the markedly different infrastructure required. A team might envision a biomimetic solution that is environmentally sustainable, in theory, but if no appropriate manufacturing techniques are at hand, realizing that solution might be impossible. The development of infrastructure required to manufacture environmentally friendly, cost-effective biomimetic products is lagging behind (Bruck et al., 2007).

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\(^1\) Exceptions always arise to a general rule. For instance, bombardier beetles defend themselves against predators by ejecting a steaming hot spray of noxious chemicals. The spray is generated internally when two chemicals, hydroquinone and hydrogen peroxide, stored in separate reservoirs in the beetle’s abdomen, are mixed in a third chamber with water and catalytic enzymes. This brings the water to a boil. Although in this case a biological organism uses extreme heat to manufacture, note that bombardier beetles generate this heat by way of a simple chemical reaction, rather than using large amounts of electricity or other external energy sources.
Nearly all biological materials are constructed of a combination of carbon, hydrogen, oxygen, nitrogen, phosphorous, and sulfur. It is the way these ingredients are combined that gives biological materials a great variety of useful functions. Industrial manufacturers take a different approach. Instead of combining a few benign elements in a multiplicity of ways to achieve a range of functional properties, we seek out rare and toxic elements like carcinogenic hexavalent chromium that inherently exhibit desired functional properties. To further illustrate this key difference consider the following: A beetle’s shell provides strength, breathability, color, and waterproofing but is made from only chitin and protein, which, in turn, are made from only the six elements previously named (Hepburn & Ball, 1973). In contrast, a chip bag is made of several different materials that each fulfills a separate function. The beetle’s shell is biodegradable, but the chip bag ends up in a landfill. To produce our own multifunctional materials from a small chemical palette, we still have much to learn about biological construction. In addition, biological manufacturing has a higher fault tolerance. Even with minor defects, natural systems are usually still fully functional. The tolerance for a discernable degree of variation would allow for fabrication noise, offering ways to create successful designs with lower production cost (Starkey & Vukusic, 2013).

One example of a promising approach to improve manufacturing is 3D printing, which involves forming a solid object from a digital model by laying down successive layers of material. This approach mimics nature’s additive, material-efficient manufacturing processes. Advances in 3D printing are unbelievably exciting, but 3D
printing processes urgently need tweaking before this technology can be considered eco-friendly. Opportunities for enhancing the technology require looking at other aspects of biological manufacturing. Right now, 3D printing uses toxic resins, ceramics, and powdered metal as feedstock (Howard, 2013), but research currently is being conducted to investigate the viability of using benign, locally sourced feedstocks, such as waste woodchips, used paper, plastic scrap, clay, or carbon dioxide (Baechler, DeVuono, & Pearce, 2013; Henke & Treml, 2013). At the end of the 3D-printed product’s lifecycle, it could be disassociated using naturally occurring enzymes, returning it to printing feedstock for 100% recycling (Howard, 2013). We can also improve 3D printing if we stick material layers together using attractive forces, such as hydrogen or ionic bonds, because such forces would eliminate the need for toxic glue between the additive layers of a 3D-printed object. Another pressing problem is the amount of energy the printing process consumes. Currently, 3D printers consume an estimated 50 to 100 times more electrical energy than injection molding to create a product of the same weight (Lipson & Kurman, 2013).

Ecosystem

Even emulating both form and process does not guarantee development of a product with a net zero or net positive environmental impact (O’Rourke, 2013). The design might still be lacking in terms of how it fits within the larger ecosystem. All organisms are part of a biome that is part of the bio-sphere. As such, every organism’s continued prosperity is dependent on the health of the biosphere (Braungart &
McDonough, 2008; McDonough, 2005). The highest level of biomimicry, emulating the ecosystem, is most difficult because it requires skilled systems thinking to make sure the design fits seamlessly within the biosphere. The US-based firm, Biomimicry 3.8 (the 3.8 stands for 3.8 billion years of evolution), developed a tool called Life’s Principles that helps evaluate a biomimetic design’s ecosystem-level sustainability. Life’s Principles summarizes repeated patterns and principles embodied by organisms and ecosystems on earth. These patterns and principles are thought to support a sustaining biosphere (Benyus, 2013). In total, the tool outlines six major principles and 20 sub-principles (see Figure 3.1). Inconsistencies with Life’s Principles are indicators of a potentially unsustainable innovation and identify opportunities to further optimize your design. These inconsistencies are easier to detect and resolve when the tool is used as a benchmark throughout the entire design process and when the team makes an effort to integrate Life’s Principles along the way.
Figure 3.1. Life’s Principles. Life’s Principles is a systems-thinking tool that contains common principles embodied by most species on Earth. Its purpose is to help practitioners create designs that fit seamlessly within the larger natural system. Permission to reprint image granted by Biomimicry 3.8.

Biomimetic designs, like all designs, can be used in a variety of ways, including those that are potentially dangerous and counterproductive. Another aspect of ecosystem-level biomimicry focuses on ensuring that biomimetic designs are used in ways that are socially beneficial. Regulating how innovations are used is not always possible, but designers still need to do what they can to ensure solutions that are deployed do “what is possible and useful” rather than “what is possible, but harmful” (Gebeshuber et al., 2009).
The Defense Advanced Research Projects Agency (DARPA) has been the biggest financial supporter of biomimicry research, as well as of the development of biomimetic concepts (Johnson, 2010). DARPA recognizes that, if understood properly, biological strategies could inform new defense capabilities. DARPA’s Defense Sciences Office (DSO) focuses on “understanding and emulating the unique locomotion and chemical, visual, and aural sensing capabilities of animals” (DARPA, 2008). DARPA’s DSO funded the development of BigDog, a dynamically stable quadruped robot that can run over rough-terrains and carry heavy loads. BigDog mimics quadruped mammal leg articulation, with compliant elements that absorb shock and recycle energy from one step to the next (Boston Dynamics, 2011). DARPA regards and values BigDog as a robotic mule to accompany soldiers in terrains too rough for conventional vehicles. Biomimetic robotic technologies like BigDog can be used in both productive and destructive ways. They can venture into remote or dangerous areas, preventing possible human injury or death. They can dismantle mines or locate survivors after a chemical disaster. On the other hand, robots can be used to illegally surveil or kill innocent civilians.

Design affects how we interface with the world, so we should balance the profound innovation possible through biomimicry with a lens of environmental and social scrutiny. This analysis requires effort on the part of the designer to selectively transfer desirable aspects of the natural model to the final design and to advocate for its

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2 Our focus here is on the technology itself. We do not provide comment on the essentiality of a military because that would reach far beyond the scope of this paper. We also assume in this discussion that the robot was made in an environmentally sustainable way, which in many cases has not yet been accomplished.
being used for positive ends. That said, the lofty ideal of net social and environmental contribution should not dissuade designers from using the biomimicry approach. A biomimetic design that does not achieve net positive effect but does improve environmental or social performance by any increment compared to the status quo is worth pursuit. Every biomimetic design is at least one stride ahead in the marathon toward a better relationship with each other and our natural environment.

Conclusion

Given our ecological plight, now is the time for designers to broaden their purpose beyond just shaping commodities according to client specifications. Designers have a unique opportunity to act as sustainability interventionists. To do so, they must adopt new forms of practice that yield sustainable solutions. Biomimicry is one such emerging practice, which involves repurposing biology’s best ideas to solve human challenges.

Biomimicry has generated designs that are environmentally and socially sustainable. Consider the success of Stabilitech, a U.K. company that has created a biomimetic technology that allows storage and handling of biological samples without refrigeration. Traditionally, biological materials, such as vaccines, have to be kept refrigerated until delivery to the patient to prevent degradation. Healthcare facilities in developing countries lacking reliable refrigeration infrastructure were forced to discard half of supplied vaccines because of problems with temperature control (Jennings & Wcislo, 2012). Some organisms—like spikemoss, tardigrades, and brine shrimp—are
able to temporarily halt their metabolism in response to adverse environmental conditions, such as extreme dryness and cold temperatures (AskNature Team, 2013; Crowe, Hoekstra, & Crowe, 1992). By mimicking the principles of biological mechanisms, Stabilitech successfully developed non-toxic and inexpensive chemical excipients that stabilize biological materials in ambient temperatures (Drew, 2008). Now viable vaccines are made available to a greater number of people in developing countries for a lower cost. And the technology is sustainable. According to a Stanford University pilot project, shifting the storage of biological samples from frozen storage to room temperature could result in energy savings of 200,000 million BTUs for refrigeration and a reduction of more than 18,000 tons in associated reduced carbon dioxide emissions over the next ten years (Jensen, 2009).

Design practitioners can set an example for others by practicing a deep form of biomimicry, which considers emulation of form, process, and ecosystem. This multilevel approach should not be limiting—it is not an all-or-nothing proposition—but is most likely to lead to solutions that awe in terms of sustainability. Much remains to be investigated and learned about biomimicry for the paradigm to mature. As more design practitioners adopt biomimicry, this development can happen more quickly. Through trial-and-error, biomimetic design practitioners can evolve best practices. As in nature’s way, maladapted strategies should rapidly disappear or transition into better-adapted ones. Every attempt at biomimicry provides value in the form of lessons learned, and regular practice will encourage a sense of responsibility to care for nature, as a mentor and source of inspiration for innovative solutions (Yen et al., 2010).
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Overview

Biomimicry, defined as innovation through the emulation of biological forms, processes, patterns, and systems, is particularly valuable for its focus on solution discovery, as opposed to solution validation. GOJO Industries, Inc., used biomimicry to drive environmentally sustainable product innovation. The approach proved both efficient and effective: in comparison to a historical new product development project with a similar objective and scope, the biomimicry driven project produced double the intellectual property and, based on a preliminary assessment of lead product concepts, at least double the energy savings for just one-sixth the resource commitment. Biomimicry also showed potential to increase the overall speed of front end innovation. This case study suggests that biomimicry may be a highly promising approach for driving...
innovation, and particularly environmentally sustainable innovation, but further investigation is needed to validate the conclusions of this single case study.

Introduction

Environmental sustainability is an increasingly important objective of product development; both growing consumer concerns and increasing regulation are forcing companies to consider how their products impact the environment. As climate change and other environmental issues have assumed greater importance, the objectives of businesses have advanced from pollution reduction to green product (Albino, Balice, & Dangelico, 2009). That is to say, focus has shifted from reducing the environmental impact of the manufacturing process—for instance by seeking third-party certified environmental management systems (for example, ISO-14001), reducing generation of hazardous waste, or cutting air emissions—to creating products that have environmentally sustainable attributes—for instance, by seeking third-party sustainability product certifications (for example, EcoLogo), increasing the use of sustainable materials, or improving energy efficiency. As R&D managers execute this shift, businesses are increasingly finding that innovation driven by environmental sustainability offers opportunities to increase competitive advantage, generate business value, and enhance customer relations (Metz, Burek, Hultgren, Kogan, & Schwartz, 2016).

A number of eco-design tools have emerged to support such green product innovation by integrating environmental considerations into product development
(Karlsson & Luttropp, 2006). These tools include guidelines such as the Ten Golden Rules, checklists like Fast Five Phillips, impact matrices such as Design for the Environment (DfE), and full life cycle assessment tools (Bovea & Pérez-Belis, 2012). But conventional eco-design tools provide only limited support for truly disruptive product innovation because they are evaluative rather than generative (Lofthouse, 2006; Petala, Wever, Dutilh, & Brezet, 2010; Vallet et al., 2013; S. Walker, 1998). In other words, they are designed to validate proposed solutions—providing analysis of the environmental performance of product concepts—rather than to explore possible solutions—generating new product concepts. For example, the DfE impact matrix might encourage a product designer to consider how a product can be disassembled easily so that each component can be recovered or recycled, or to look at using alternative materials that are more recyclable than those that might previously have been used. These kinds of considerations come into play only after a relatively well-developed product concept has been formulated.

Eco-design tools would be more likely to drive green product innovation if they could be introduced in the solution discovery phase, also known as the fuzzy front end of innovation (Koen et al., 2002). Early in the product development process, while ideas are still being introduced and shaped, there is greater flexibility to incorporate environmentally sustainable attributes and to reconsider basic attributes; waiting until later phases, when the solution approach has been determined and the most critical technical decisions have already been made, can limit designers and engineers to
incremental improvements or rule out the possibility of including desirable environmental characteristics altogether (Bovea & Pérez-Belis, 2012).

One lesser known eco-design tool that is suitable for introduction in the front end of innovation is biomimicry. Biomimicry is defined as the technical emulation of biological forms, processes, patterns, and systems (Benyus, 2013). As an innovation approach, it is based on the belief that natural selection favors high-performance, resource-efficient survival strategies—strategies that can be copied to address technical challenges. The redesign of Japan’s 500 Series Shinkansen Bullet Train is an example of biomimicry. Before it was redesigned, the train, which reaches speeds up to 200 miles per hour, caused air pressure to build up in tunnels, which then created a sonic boom every time the train exited a tunnel. People living up to 15 miles away complained about the noise. The engineers tasked with redesigning the train’s nose to reduce noise modeled their new design after the beak of the kingfisher, a bird that dives head first into water, a denser medium than air, without making a splash. The new train is quieter than the original model, meeting the goal of the project; it is also 10 percent faster and runs on 15 percent less electricity (Benyus, 2009). A number of examples demonstrate biomimicry’s potential specifically to drive environmentally sustainable innovation. One company has created an environmentally friendly calcium carbonate powder inspired by coral’s carbon dioxide–fixing process; the powder can replace a portion of Portland cement in traditional concrete mixes to reduce cement’s carbon footprint (Lurie-Luke, 2014). Another has created carpet tiles inspired by the organized chaos of a forest floor. The tiles’ pattern and coloration allows for nondirectional installation, which is much

40
faster and less wasteful—reducing waste from up to 14 percent for traditional broadloom carpet to as little as 1.5 percent (Interface, Inc., 2016). And the photosynthetic process has inspired design of cheap, energy-efficient solar cells made of inexpensive, eco-friendly materials (Reece et al., 2011).

To clarify, biomimicry does not necessarily yield environmentally sustainable solutions. However, practiced thoughtfully in the context of clear performance goals for environmental sustainability, it can be a powerful design tool that supports sustainability-driven innovation in the front end of innovation (Kennedy et al., 2015). Indeed, drawing on estimates of biomimicry’s penetration in various industries, Fermanian Business & Economic Institute predicts that by 2030, biomimicry could account for $425 billion in US GDP and $1.6 trillion in global GDP, as well as generating savings associated with reduced resource depletion and pollution (Fermanian Business & Economic Institute, 2013).

Despite its tremendous promise, however, awareness of biomimicry and the principles guiding its practice remains limited among R&D professionals. Little has been published on best practices, which limits understanding and effective use of biomimicry (Nagel & Stone, 2012; Vincent, Bogatyreva, Bogatyrev, Bowyer, & Pahl, 2006). GOJO, a manufacturer of skin health and hygiene solutions, implemented biomimicry in its new product development process, with promising results. The biomimicry process significantly streamlined the front end of innovation, producing more intellectual property for a much smaller resource commitment—and at the same time offered product designs that promise significant energy savings. Though this is only a single
case, the results suggest biomimicry could advance green product innovation while providing a high return on investment.

Developing a Better Soap and Sanitizer Dispenser Using Biomimicry

GOJO has a long history of bringing innovations to the hand hygiene market, including patenting the first portion controlled soap dispenser in 1952, bringing the first sanitary sealed soap dispenser refills to commercial markets in 1983, and launching PURELL, the first alcohol-based hand sanitizer, in 1997. As part of its strategic approach to innovation, GOJO engages in technology- and capability-building partnerships with universities and other organizations. That history of collaboration led Great Lakes Biomimicry to approach the company in 2012 regarding a potential partnership in which GOJO, Great Lakes Biomimicry, and the University of Akron would sponsor an industrial assistantship program in Biomimicry for a PhD Fellow. The goal of the program was to embed biomimicry in the R&D organization and throughout the company over the five-year course of the fellowship. Believing that biomimicry could advance enterprise goals related to innovation and create sustainable value, GOJO’s leadership accepted the invitation.³

In 2013, as it contemplated development of its next generation of liquid soap and sanitizer dispensers, the company turned to its Biomimicry PhD Fellow to integrate

³ We use the term sustainable value as it is defined by Laszlo (2008): sustainable value yields economic, social, and environmental gains for the enterprise and its stakeholders. It is about making business decisions that both benefit people and are nondestructive, and ideally that are supportive of the planetary ecosystem.
biomimicry into the development process. Liquid soap and sanitizer dispensing systems provide a dosed amount of product upon actuation. These dispensing systems are installed in schools, restaurants, hospitals, manufacturing facilities, fitness centers, office buildings, and other high volume, public settings. For its new generation of dispensers, GOJO turned its attention to the environmental sustainability of these ubiquitous systems. With this in mind, the company conducted a full lifecycle assessment for its most advanced touch-free dispensing system, which showed that the batteries in the system were responsible for much more of the system’s environmental impact than other components—four times more, in fact, than was accounted for by the manufacturing of all the refill pumps the dispenser would need throughout its entire life. This finding indicated that increasing the energy efficiency of the pump would likely be the most effective way to reduce the system’s environmental impact, with likely environmental benefits exceeding the improvements that could be yielded by other approaches, such as incorporation of recycled content or dematerialization of the pump.

To generate ideas for ways to reduce the system’s energy usage, the product development team turned to biomimicry. Low-energy survival strategies are prevalent in the biological world. Technological solutions tend to rely on energy inputs to achieve a functional goal; biological solutions, on the other hand, tend to leverage information transfer and hierarchical structures (Bogatyrev & Bogatyreva, 2009b; T. McKeag, 2013). For example, Kevlar, a high-performance synthetic fiber, is formed by an energy-intensive chemical reaction that occurs at high temperatures, while spider silk, a natural
fiber up to 10 times tougher than Kevlar, is formed at room temperature using water-based chemistry.

A cross-functional team of 15 GOJO employees with organizational roles spanning engineering, biology, chemistry, design, marketing, and sustainability volunteered to tackle this challenge. In total, these 15 employees dedicated 165 hours to three collaborative workshop sessions co-led by the PhD Fellow and independent interim work. The goal of the first workshop session was to create a solution neutral functional representation of the R&D challenge, intended to help the participants focus on a wide range of relevant solutions by stripping the problem of any distracting concrete attachments. This is the equivalent of re-representing the hypothetical challenge of designing a more effective toothbrush as the challenge of improving mouth hygiene. The team was introduced to biomimicry tools that support functional representation using biological terms, such as the Biomimicry Taxonomy (Biomimicry 3.8, 2013a), and an Engineering-to-Biology Thesaurus (Nagel, Stone, & McAdams, 2010). The Biomimicry Taxonomy is a three-tiered hierarchy of functions represented in biology. The technical challenge of dispensing soap fits in the overarching taxonomy category Get, Store, or Distribute Resources, in the subcategory Distribute, and in the narrowest nested category Distribute Fluid. The Engineering-to-Biology Thesaurus maps engineering function terms to their biological function correspondents. For example, biological synonyms for the engineering function “dispense” include “excrete” and “transfer.” The team used these tools to reframe the primary challenge as fluid distribution or fluid transfer.
Team members then dispersed to use the functional representation to independently identify relevant biological models, through keyword searches of biological databases, exploration of nature documentaries, and immersion in a natural environment. All were encouraged to access and summarize peer-reviewed articles on the biological models they identified with the help of GOJO colleagues who had biological expertise (as a skin health and hygiene company, GOJO employs many microbiologists) or external subject matter experts. For some individuals, the breadth of the guiding question—How do biological systems distribute or transfer fluids?—was daunting. These individuals typically adopted more focused frames of inquiry, which were self-generated, to make sifting through an expanse of biological information more manageable (Table 4.1). These frames of inquiry might also be referred to as research lenses.

Table 4.1. Frames of inquiry adopted by members of the product development team to identify relevant biological models

<table>
<thead>
<tr>
<th>Frame of Inquiry</th>
<th>Assumption</th>
<th>Resulting Focus</th>
</tr>
</thead>
<tbody>
<tr>
<td>Similar context: What biological models exist in a context similar to the problem context?</td>
<td>Biological models inhabiting environments similar to the problem context will adopt strategies that may be relevant to the problem.</td>
<td>Models living in environments where there is persistent fluid movement (i.e., cilia lining Animalian breathing tubes, which move mucus from the lungs to the throat).</td>
</tr>
<tr>
<td>Extremes: What biological models deal with extreme versions of the problem?</td>
<td>Biological models most challenged by the problem will embody the most robust strategies for addressing it.</td>
<td>Models living in regions with extremely high-volume fluid influx (i.e., sphagnum moss growing on the rainforest floor, which must manage high annual rainfall).</td>
</tr>
<tr>
<td>Convergence: What biological strategy for accomplishing the function of interest is used by many, distantly related species?</td>
<td>A strategy independently evolved in different contexts is likely to be a beneficial approach.</td>
<td>Winged flight, a fluid (air) passage strategy, independently evolved by birds, bats, and insects.</td>
</tr>
<tr>
<td>Stasis: What biological strategy for accomplishing the function of interest has persisted over time?</td>
<td>A strategy that has been conserved through evolution is likely to be effective and difficult for competitors to defeat.</td>
<td>Underwater locomotion of the chambered nautilus, a pelagic marine mollusk that has remained morphologically constant for ~400 million years.</td>
</tr>
</tbody>
</table>

The second workshop session was devoted to reporting on these independently identified biological models and extracting their design principles—abstract representations of the biological phenomena embodied by the models. Formulating appropriate design principles is a fundamental hurdle in biomimicry (Nagel et al., 2010).
Practitioners often skip this critical step, fixate on biological entities (Cheong & Shu, 2013), and transfer surface features to a solution without appropriate abstraction (Linsey & Viswanathan, 2014; Mak & Shu, 2004). To borrow an extreme example from Helms et al. (2009), a biomimicry practitioner designing a device to shell peanuts, lacking an appropriate abstract representation, might suggest training squirrels to shell the peanuts. Clearly, such direct transfer of the biological actors is not practical or sustainable and will not result in a marketable solution.

What is needed in place of a direct application of the biological model is an analogous concept that works in accordance with abstract design principles derived from the biological model. Extracted design principles should capture the essence of the biological strategy and translate it in a way that is biologically accurate but free of biological jargon, enabling non-biologists to use it as a stimulus for ideation (Baumeister, 2014). Design principles should also be generalized as much as possible, eliminating irrelevant specifics that do not apply to the functional problem (Sartori et al., 2010).

Guided by these principles and with live facilitation by the PhD Fellow, the GOJO innovation team extracted a number of design principles from the biological models proposed (Table 4.2). Nearly 40 models were proposed, more than could be profitably explored in a relatively brief workshop. The list was winnowed to about a dozen, based on how well the team understood particular models or how easily additional information needed to sufficiently explain the mechanisms at play in a proposed model could be accessed. Publications heavy with biological jargon were difficult for many team members to parse; even the more accessible literature often described a biological
behavior (the what) without adequately detailing its underlying mechanics (the how). A fundamental understanding of how the proposed biological model accomplished fluid distribution/fluid transfer behavior provided a necessary base for extracting design principles.

Table 4.2. A selection of biomimetic design principles relevant to the fluid distribution/fluid transfer problem

<table>
<thead>
<tr>
<th>Model</th>
<th>Biological Description</th>
<th>Design Principles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertebrate arteries</td>
<td>Conducting arteries have elastic walls that expand to accommodate blood pumped by the heart during systole and relax during diastole, propelling blood onward. The elasticity of artery walls dampens flow pulsatility.</td>
<td>• The wall of an elastic reservoir functions as an energy capacitor when stretched.</td>
</tr>
<tr>
<td>Xylem in plants</td>
<td>Several synergistic mechanisms allow vascular plants to transport water against gravity: cohesion (the attractive force among water molecules) and adhesion (the attractive force between water molecules and the xylem walls) allow plants to draw water up from the root like a rope, and transpiration, vaporization, and release of water into the atmosphere at the leaf's surface generate a pressure gradient that exerts an upward pull on the water column in the xylem channel.</td>
<td>• Cohesive/adhesive fluids can be pulled upward through narrow tubes without breakage in the fluid column.</td>
</tr>
<tr>
<td>Archedfish</td>
<td>The archerfish spits a jet of water to knock its insect prey into the water. Although the fish can exert a max force of 500 watts/kg, the jet strikes the prey with a force of 3,000 watts/kg due to Rayleigh-Plateau instability and kinematic gathering: the back end of the cylindrical jet moves towards the front end to form a compact globule, resulting in acceleration of the jet in the air.</td>
<td>• An elongated liquid that is in motion tends to amass and accelerate due to surface tension.</td>
</tr>
<tr>
<td>Squid locomotion</td>
<td>A squid moves by enlarging the intake to its mantle cavity so that the cavity rapidly fills with water, then contracting the cavity, forcing water out a rear-facing funnel tube.</td>
<td>• The larger the flow area of an intake valve, the lower the pressure differential required to pull fluid in to fill a cavity.</td>
</tr>
<tr>
<td>Rove beetles</td>
<td>To skim across water with speed, the semiaquatic rove beetle secretes a superhydrophobic substance that repels water, thereby propelling the beetle.</td>
<td>• Significant force is generated when one material comes in contact with another that repels it.</td>
</tr>
<tr>
<td>Cilia</td>
<td>Cilia are minute, hair-like organelles that beat in rhythmic waves, providing locomotion to ciliate protozoans and moving liquids along internal epithelial tissue in animals. The row stroke of a cilium is nonreciprocal, producing a net propulsive force in the wave direction.</td>
<td>• A flexible appendage with an optimized row stroke can produce a net propulsive force.</td>
</tr>
</tbody>
</table>

Team members were then charged to use the list of extracted design principles as stimulus for independent ideation of novel soap and sanitizer dispenser concepts. In the third workshop session, participants reported on their preliminary concepts and collaborated to enrich top concepts. Top concepts were chosen according to the criteria of novelty, perceived feasibility, and potential value with regard to environmental sustainability. The process of independent ideation and subsequent collaborative selection and enrichment of top concepts followed a “diverge then converge” approach.
supported by creativity and innovation research (Thompson, 2003). After the conclusion of the workshop, GOJO engaged contract design services to further develop 20 leading concepts.

Ultimately, this effort resulted in four patent applications for novel dispensing systems. These solutions promised to generate sustainable value from a number of sources even beyond the energy-use reductions that were the primary goal (Table 4.3). One novel design that emerged from this process, the double-acting bladder pump, was inspired by the heart, a multichambered biological pump with common walls (Figure 4.1). Like the heart, the double-acting bladder pump has separate elastomeric chambers walled off from each other by a central spine that incorporates fluid inlet and outlet valves. Coupled drive arms are used to actuate the pump. Energy recaptured from the recovery cycle of one chamber helps compress the other chamber. This bio-inspired technology provides an estimated 50 percent energy savings compared to analogous pumps currently used by GOJO, with potential for up to 80 percent energy savings when combined with optimized valves and product formulations.

Table 4.3. Potential sources of sustainable value in biomimicry-based dispensing system technologies

<table>
<thead>
<tr>
<th>Technology</th>
<th>Primary Inspiration</th>
<th>Material Optimization</th>
<th>Environmental Sustainability Improvements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Double-acting bladder pump</td>
<td>Human heart</td>
<td>Parity with current solutions</td>
<td>Less energy used per wash (energy of one chamber recovering helps compress sympathetic chamber)</td>
</tr>
<tr>
<td>Elastic bladder dispenser</td>
<td>Vertebrate arteries</td>
<td>Reduced weight</td>
<td>Less energy used per wash (energy stored in stretched bladder wall used to eject product)</td>
</tr>
<tr>
<td>Pillow bag with integrated foam</td>
<td>Squid locomotion</td>
<td>Reduced part count</td>
<td>Parity with current solutions</td>
</tr>
<tr>
<td>Pressurized, collapsible liquid</td>
<td>Xylem in plants</td>
<td>Parity with current solutions</td>
<td>Less energy used per wash (air pressure vs. mechanical force facilitates collapse)</td>
</tr>
<tr>
<td>container</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
GOJO Industries Comparative Case Study

The quantity and quality of intellectual property generated by the biomimicry project, in terms of both potential sustainable value and technological novelty, was impressive, especially given the low resource investment—just 165 total hours committed by internal personnel. In an effort to capture the extent of the advantages offered by biomimicry, we compared the biomimicry project’s performance in terms of resource commitments and outcomes to a similar pump development project GOJO executed in 2010. The historical pump project had similar goals—to develop a low-cost, energy-efficient, smaller, and more easily recyclable pump than the existing model in
the market—and a comparable scope to the biomimetic pump project. The key difference between the two projects was the approach to solution discovery in the fuzzy front end, regarded as one of the biggest opportunity areas for improving the innovation process (Koen et al., 2002). In the historical project, the front end process began with assessing the intellectual property (IP) landscape both within the industry (that is, peristaltic soap pumps) and in analogous industries (for instance, beverage dispensing technologies in the food industry). Patentable solutions were then generated by bridging gaps in existing IP and combining existing technologies in novel and useful ways. In comparison, the approach to solution discovery during the biomimicry project involved identifying relevant biological models and extracting design principles embodied by those models to use as ideation stimuli. The concepts based on those design principles were then screened for prior art.

Data for the quantitative comparison were collected by reviewing internal project documentation and crosschecking the currency and accuracy of those documents by interviewing employees who were involved in one or both projects. The results of our analysis suggest that biomimicry can be a much more efficient way to generate useable concepts in the early stages of product development. The biomimicry project required approximately one-sixth of the personnel and financial resources required by the historical project and produced double the intellectual property to reach the same stage of development as the historical project; the concepts resulting from the biomimicry project offered an estimated double to quadruple the energy savings of those emerging from the historical project, as well (Table 4.4). Additionally,
a greater proportion of the concepts emerging from the biomimicry project converted from notices of invention to patent applications. (Two remaining notices of invention from the biomimicry project are still under consideration.) These preliminary data strongly suggest that biomimicry may offer real advantages in the front end of innovation, both for improved innovation performance and for improved sustainability.

Table 4.4. Comparative resource commitments and outcomes, biomimicry case vs. historical project

<table>
<thead>
<tr>
<th></th>
<th>Biomimicry Project</th>
<th>Historical Project</th>
</tr>
</thead>
<tbody>
<tr>
<td>Man Hours</td>
<td>285</td>
<td>1620</td>
</tr>
<tr>
<td>Total Cost</td>
<td>$23,000</td>
<td>$129,000</td>
</tr>
<tr>
<td></td>
<td>$13,000 Employee time</td>
<td>$100,000 Employee time</td>
</tr>
<tr>
<td></td>
<td>$10,000 Contracted design services</td>
<td>$29,000 Contracted design services</td>
</tr>
<tr>
<td>Notices of Invention</td>
<td>6</td>
<td>5</td>
</tr>
<tr>
<td>Patent Applications</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>Lead Concept Energy Savings</td>
<td>50%–80%*</td>
<td>20%**</td>
</tr>
</tbody>
</table>

*engineering estimate
**prototype performance data

IP landscaping, the solution discovery approach used in the historical project, was more time consuming than the biomimicry project, tended to produce more incremental designs, and did not integrate sustainability as closely in the concepts generated. The biomimicry approach, presumably because it used models of sustainable systems as sources of ideas, resulted in more sustainable, often more radical product concepts. IP landscaping can complement the application of biomimicry as a secondary validation step in the front end, but IP landscaping alone did not, in our cases, offer the same results as biomimicry.

Structured interviews with two engineers who participated in both the biomimicry and the historical project provided additional qualitative insights on the two
processes. Both of the engineers interviewed are longtime employees with solid innovation track records (more than 70 patents between them). Their responses suggest that biomimicry significantly accelerated the front-end development process and improved the quality of the concepts emerging from it. Engineer One said,

“The speed of coming up with new, innovative concepts increased dramatically with the biomimicry approach. Totally new concepts came out of that process versus concepts that had some nuance but weren’t completely novel.”

Similarly, Engineer Two told us,

“The resource drain [with the biomimicry project] was far less [than with a typical pump development project] . . . The stimuli were completely different and allowed for completely unique ideas rather than building upon prior art.”

These remarks confirm empirical findings from other researchers (Wilson et al., 2010) that suggest that exposure to biological analogies during idea generation may increase the novelty of design ideas.

Their participation in the biomimicry project also had long-term implications for the engineers’ approach to innovation. Asked what learnings from the biomimicry project they had carried forward in their work, the engineers offered detailed responses. Engineer One said that biomimicry:

“...pushed us to look beyond the initial project scope and not just look at the pump technology but look at the overall system—the packaging, the actuation—in order to optimize the whole product. Looking at the overall system is something I’ve carried forward from that approach.”

Engineer Two focused on the efficiency of the approach, suggesting that when innovators:

“...follow nature, nonobvious decisions are made obvious or more attainable. The [heart-inspired double-acting bladder pump] concept was remarkably simple, but would not have been obvious without using biomimicry. Biomimicry
cuts down on the number of product innovation iterations we would typically go through.”

Engineer One’s response suggests that biomimicry encourages systems thinking. This makes intuitive sense, since biological systems tend to leverage low part-count, multifunctional designs (Baumeister, 2014). These multifunctional biological mechanisms preclude innovators from considering one component of a system in isolation. Thus, biomimicry helps innovators understand and leverage the interdependencies of system components, as previous researchers have suggested (Seebode, Jeanrenaud, & Bessant, 2012).

Further, our observations of project participants during workshops and of the engineers in the follow-up interviews suggest an additional hypothesis: that biomimicry is intrinsically motivating. Intrinsic motivation—defined as interest, enjoyment, and satisfaction in work itself—is positively correlated with higher levels of creativity (Hennessey & Amabile, 2010a). Verbal and nonverbal cues from participants in the biomimicry project (describing the work as “fun” and “cool,” laughter, smiling, and attentive posture during the workshops) suggest they were highly engaged in the process, particularly during the reporting of the independently identified biological models. If this hypothesis can be backed by empirical data confirming that biomimicry is intrinsically motivating, and therefore heightens levels of creativity, the finding would be a powerful motivator for more widespread adoption of biomimicry in product development.
Discussion

Biomimicry, as implemented at GOJO Industries, generally comprised five phases: 1) Problem definition; 2) Specification of desired functions; 3) Identification of biological models exemplifying desired functions; 4) Extraction of design principles embodied by biological models; and 5) Ideation of biomimetic solutions using design principles as stimulus. This multiphase process is not intended to be prescriptive, but it does provide a malleable template other R&D managers may adapt to their own organizations and processes. Specifically, managers can find ways to integrate biomimicry with existing approaches to innovation in the front end, such as IP landscaping, to maximize return on investment. To implement the template effectively, managers will need to think in advance about how to address the breadth of potential biological models, the accessibility of biological literature, and the challenge of extracting well-formulated design principles.

Conclusion

Our study of GOJO’s approach to biomimicry in the front end of innovation suggests the potential biomimicry may offer to accelerate solution discovery in the front end of innovation. It also suggests biomimicry’s ability to drive environmentally sustainable innovation, a finding worth highlighting given the challenges currently faced by industry with regard to sustainability. A relationship between the thoughtful practice of biomimicry and generation of green product concepts makes intuitive sense, given that natural selection favors biological strategies fit for life on earth over the long haul.
Further work is warranted to determine how and to what extents our results are generally applicable. Even without that further research, however, this study stands as justification for R&D practitioners to try biomimicry in their organizations by illuminating its potential as a low-risk experiment with a potentially very high return on investment. In short, biomimicry is a highly promising approach meriting further investigation by R&D leaders and researchers alike.

Acknowledgements

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CHAPTER V

INDUSTRY PRACTICE OF BIOINSPIRED DESIGN:
DO FRAMES OF INQUIRY SUPPORT SEARCH AND IDENTIFICATION OF BIOLOGICAL MODELS?

In Progress:

Kennedy, E. B. and Niewiarowski, P. H. In Progress. Industry Practice of Bioinspired Design: Do Frames of Inquiry Support Search and Identification of Biological Models?

Abstract

A crucial step in the bioinspired design process is search and identification of biological models relevant to the design challenge. Anecdotal observations from case studies in authentic business contexts, as well as emerging literature on bioinspired design methods, suggest that tools which focus the search for biological models could help R&D professionals execute this step more effectively. We prototyped one such tool, a set of four narrowed frames of inquiry, to test whether it helped R&D professionals identify a greater quantity and variety of biological models. Conducting an experiment with R&D professionals undertaking a real design challenge, we found that our prototyped tool did not have a significant positive effect on biological model identification. Trends of higher quantity biological models identified were observed for participants provided the four frames, but high variance among groups within
treatments gave our tests low power. Because previous work, both empirical and theoretical, suggests that tools like ours should optimize search and identification of biological models, we believe further tests with larger samples and/or conditions which maximize potential effect sizes, are warranted. We argue that experimental studies such as ours, using R&D professionals undertaking real design challenges, are difficult but necessary to advance bioinspired design.

Introduction

Bioinspired design (BID) can be defined as innovation through emulation of biological forms, processes, patterns, and systems (Benyus, 2013). BID is based on the idea that natural selection tends to favor highly adapted and differentiated survival strategies—strategies that can be translated to address technical challenges. VELCRO®, an adhesive system inspired by how burrs cling to animal fur, is an example of BID (Jenkins, 2012). Despite the potential to deliver radical, environmentally sustainable product innovations (Kennedy & Marting, 2016; Lurie-Luke, 2014), little has been published on best practices for BID apart from a few important studies carried out with students in classroom settings (Goel et al., 2015, 2012; Wilson et al., 2010; Yen et al., 2010). Notably absent in the literature are empirical studies designed to support and inform development of procedural scaffolding for industry practice of BID. This limits understanding and effective implementation in such contexts (Nagel & Stone, 2012; Julian F.V. Vincent et al., 2006). The purpose of this study is to contribute to development of best practices for BID in industry settings. It should be clarified that the
intention is not to strictly standardize BID processes, but to provide practical, evidence-based recommendations that will inform lesson planning for professional education and promote effective implementation of BID in business.

A BID industry case study (Kennedy & Marting, 2016) provided motivation for the current study. The goal of the industry project was innovation of energy-efficient liquid soap and sanitizer dispensers. BID, as implemented in this industry case, generally comprised five iterative phases: 1) problem definition; 2) specification of desired function(s); 3) identification of biological models exemplifying desired function(s); 4) extraction of design principles embodied by biological models; and 5) ideation of biomimetic solutions using design principles as stimulus. The desired function specified for the liquid soap and sanitizer dispensing challenge was fluid distribution or transfer. Thus, “How do biological models distribute or transfer fluid?” was the research question project participants in this industry case used to query biology. The breadth of this research question overwhelmed some project participants. Typically, these participants attempted to narrow their searches using self-generated ‘frames of inquiry’ (Table 5.1), hereafter termed ‘frames.’ Frames were heuristics that tightened the field of view to make sifting through an expanse of biological information more manageable (Emily B. Kennedy & Marting, 2016). Implementing a narrower scope to facilitate identification of biological models in BID is a behavior consistent with innovation research that suggests a brainstorming problem presented as a series of separate questions, versus one all-encompassing question, results in greater quantity and variety of ideas because it refocuses attention more evenly across the entire
problem (Dennis, Valacich, Connolly, & Wynne, 1996). Tools that help focus attention during search for analogous solutions in distant domains, like biology, have a particularly important role to play (Linsey, Wood, & Markman, 2008).


<table>
<thead>
<tr>
<th>Frame of Inquiry</th>
<th>Assumption</th>
<th>Hypothetical Challenge</th>
<th>Resulting Focus</th>
</tr>
</thead>
<tbody>
<tr>
<td>Similar context: What biological models exist in a context similar to the problem context?</td>
<td>Biological models inhabiting environments similar to the problem context will adopt strategies that may be relevant to the problem.</td>
<td>Wet Adhesion</td>
<td>Models that affix in wet environments (i.e., mussels)</td>
</tr>
<tr>
<td>Extremes: What biological models deal with extreme versions of the problem?</td>
<td>Biological models most challenged by the problem will embody the most robust strategies for addressing it.</td>
<td>Stormwater Management</td>
<td>Models living in regions with high annual rainfall (i.e., sphagnum moss growing on the rainforest floor)</td>
</tr>
<tr>
<td>Convergence: What biological strategy for accomplishing the desired function is used by many, distantly related species?</td>
<td>A strategy independently evolved in different contexts is likely to be a beneficial approach.</td>
<td>Location Tracking</td>
<td>Sonar-like echolocation, independently evolved by bats, toothed whales, and shrews</td>
</tr>
<tr>
<td>Stasis: What biological strategy for accomplishing the desired function has persisted over time?</td>
<td>A strategy that has been conserved through evolution is likely to be effective and difficult for competitors to defeat.</td>
<td>Dynamic Buoyancy</td>
<td>The chambered nautilus, a marine mollusk whose form has remained largely unchanged for ( \sim 400 ) million years</td>
</tr>
</tbody>
</table>

Some of the frames generated by participants in the BID industry case study (Kennedy & Marting, 2016) are traceable to biological model search recommendations made in BID practitioner texts. For example, the Biomimicry Resource Handbook: A Seedbank of Best Practices encourages practitioners to focus their search for biological models “on contexts similar to the project’s context” (Baumeister, 2014). This directive corresponds to our “similar context” frame (Table 5.1). The Biomimicry Resource
Handbook also recommends that practitioners look for “organisms that are most challenged by the problem you are trying to solve, but remain unfazed by it” (Baumeister, 2014). This directive corresponds to our “extremes” frame (Table 5.1). Support for our remaining frames comes from various sources associated with BID and biological research. For example, Yen et al. (2010) provides a basis for our “convergence” frame (Table 5.1), asserting that “convergent evolution, where organisms from completely different lineages arrive at the same solution to similar conditions is one means to identify key biological mechanisms that may be useful for engineered design.” Similarly, biological examples of apparent conservation of morphology or other characteristics of so-called “living fossils” provides basis for our “stasis” frame (Table 5.1). As Werth and Shear (2014) note, “a key innovation renders living fossils successful in persisting for long stretches of time,” and, “just as wide-moat companies are good bets for investors seeking continued performance, living fossils yield strong long-term returns.”

In BID, frames function as heuristics—practical discovery devices aimed at improving search and identification of biological models among R&D professionals. Frames are not intended to capture the precise detail and complexity of evolutionary theory, but that is a dimension of their utility; it is what makes them accessible to non-biologists. Despite the application of frames during BID (Kennedy & Marting, 2016), as well as their promotion in some practitioner texts, no study has yet investigated whether providing frames actually improves search and identification of biological models relevant to a particular design challenge. Such evidence could be important
since the identification of biological models exemplifying desired function(s) is one of the major challenges of BID (Gruber, 2016). Other challenges include the resourcing of information about identified models (Kennedy & Marting, 2016) and selection of the most informative models from the initial collection (Gruber, 2016). Identification of biological models is the challenge of focus in this study as it is nearest the front end of the BID process. The front end is regarded as one of the biggest opportunity areas for improving an innovation process (Koen et al., 2002). In this study, we were particularly interested in investigating the following:

1. **Capacity for identifying biological models:** We hypothesized that the quantity and variety of biological models identified would be greater for teams provided the four frames outlined in Table 5.1 compared to teams not provided frames;

2. **Frames Cited:** We hypothesized that: 1) the variance in number of frame citations among teams provided frames would be influenced by the assigned search objective, suggesting usefulness of frames is problem-dependent, and that 2) certain frames would be cited more often than others, potentially indicating greater utility; and

3. **Influence of Demographics:** We explored whether variation in several demographic factors was associated with team results and individual perceptions about the exercise.
Methods

A study of 91 R&D professionals and summer interns was conducted on July 15, 2015, at the Akron Zoo (located in Akron, Ohio, United States) during the participating company’s annual offsite R&D department teambuilding event. The 50-acre Akron Zoo is home to over 700 animals and 7,000 plants and flowers. Attendees (n=91) were familiarized with the concept of BID via a 30-minute introductory presentation delivered by one of the study’s authors and then randomly assigned by event organizers to one of 12 seven- or eight-person teams, the average size of working groups at the participating company. Six of the 12 teams were instructed to ‘search and identify biological models for attachment, including temporary attachment and attachment to irregular surfaces’ (Search Objective 1). Resulting biological models were expected to be relevant to innovation of versatile mounting brackets for soap and sanitizer dispensers. The remaining six teams were instructed to ‘search and identify biological models for sealed storage/liquid containment’ (Search Objective 2). Resulting biological models were expected to be relevant to innovation of wearable soap and sanitizer dispensers. Each team was assigned a process coach who received verbal and written instruction on how to keep the team on task throughout the exercise (Table 5.2).
Table 5.2. Process coach instructions for BID study.

<table>
<thead>
<tr>
<th></th>
<th>Instructions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Remind team, as necessary, that they have been instructed to identify, and record in legible handwriting, as many biological models as possible.</td>
</tr>
<tr>
<td>2</td>
<td>Remind team, as necessary, to visit as many exhibits as possible.</td>
</tr>
<tr>
<td>3</td>
<td>Remind team, as necessary, that a ‘biological model’ includes biological organisms from all kingdoms (animals, plants, etc.); biological forms, processes, patterns, or systems.</td>
</tr>
<tr>
<td>4</td>
<td>Remind team, as necessary, that they should not discuss their handout outside of their team.</td>
</tr>
<tr>
<td>5</td>
<td>Encourage all team members to participate.</td>
</tr>
<tr>
<td>6</td>
<td>Do not identify biological models for the team.</td>
</tr>
<tr>
<td>7</td>
<td>If your team is the recipient of Handout 2, make no attempt to explain provided frames.</td>
</tr>
<tr>
<td>8</td>
<td>Wrap at 60 minutes and collect completed handouts.</td>
</tr>
<tr>
<td>9</td>
<td>Lead your team to the picnic area where you will provide a survey to everyone on your team and ask them to complete it.</td>
</tr>
<tr>
<td>10</td>
<td>Remind survey respondents to be honest and thorough.</td>
</tr>
</tbody>
</table>

Teams spent 60 minutes exploring zoo grounds with their process coach, searching and identifying biological models relevant to their assigned search objective. Prior to being dispatched, three of the six teams assigned to Search Objective 1 and three of the six teams assigned to Search Objective 2 were given copies (two per team\(^4\)) of Handout 1 (Appendix A). This handout instructed participants to search and identify as many biological models as they could within the allotted 60 minutes guided by the basic BID research question “How do biological models accomplish the desired function(s)?” These teams represent the control group. Remaining teams were given copies (two per team) of Handout 2 (Appendix A). This handout instructed participants to search and identify as many biological models as they could within the allotted 60

\(^4\) The purpose of providing each team with two copies of their respective handouts was to allow for two people to simultaneously record data and provide ample space. A single copy of Handout 1 or Handout 2 provides space for recording 12 biological models. Across two copies each team had space to record 24 models, a number that well exceeded the total researchers expected any team to identify in 60 minutes.
minutes guided by the frames. These participants were further instructed to code each biological model by which frame helped lead to its identification [F1, F2, F3, F4]. These teams represent the experimental group.

Table 5.3. Experimental design matrix.

<table>
<thead>
<tr>
<th>Handout 1 (Control)</th>
<th>Search Objective 1</th>
<th>Search Objective 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3 teams</td>
<td>3 teams</td>
</tr>
</tbody>
</table>

| Handout 2 (Experimental) | 3 teams | 3 teams |

The process coach, in addition to keeping his team on task, simultaneously filled the role of observer during the 60-minute search period, recording observations of group behavior. Process coaches were instructed to record anything deemed noteworthy, paying particular attention to: 1) any observed discussion of handouts with other teams (counter to instructions); 2) instances in which their team was within earshot of another, and could have overheard ideas; 3) any observed power relationships that may have inhibited openness/participation of some team members; and 4) for teams in the experimental group, the extent to which a vocal group leader may have unduly influenced how much time was spent considering each frame. These observations were collected as a means of disqualifying erroneous data.

After 60 minutes, all teams congregated at the Akron Zoo’s picnic area and submitted completed handouts. Then, individuals were asked to complete one of two brief, anonymous surveys depending on whether their team was provided frames or not. Individuals from teams in the control group (no frames), were administered Survey 1 (Appendix A). Individuals from teams in the experimental group (frames), were administered Survey 2 (Appendix A). The surveys asked individuals about their
gender, age, educational attainment, disciplinary background, assigned search objective, level of familiarity with BID, and perceived difficulty of the exercise. The survey provided to individuals from teams in the experimental group also asked what other frames of inquiry, in addition to the four provided, might support search and identification of biological models. Individuals submitted completed surveys and a brief group discussion followed. Participants were informed of the differences between the control and experimental treatments and asked: What do you think was the impact of providing frames to some groups?

Completed handouts, process coach observations, survey responses, and audio recording of the brief group discussion comprise quantitative and qualitative data analyzed to investigate quantity and variety of models generated, frames cited, and the influence of demographics. We used ANOVA when testing if means differed between control and experimental groups (i.e. quantity models generated, variety models generated, frames cited, and perceived difficulty), and a chi-squared test to compare the distribution of frames cited between control and experimental groups. Finally, we explored the influence of demographic variables (e.g., gender, age, educational background) on participant’s qualitative perceptions about the exercise using forward stepwise regression (JMP® 12).

Results

Process coaches observed teams adhering to instructions. Teams did not discuss content of handouts with other teams. There were instances in which teams crossed
paths between exhibits, but no two teams ever occupied the same exhibit. Thus, while overhearing another team’s ideas was possible, we believe any effect is negligible. With process coach encouragement, there was reasonably balanced team member participation with no single, dominant voice on any team. Therefore, no data were disqualified as erroneous.

**Capacity for Identifying Biological Models**

The control group (no frames) produced an average of 15.5 biological models per team, compared to 17.8 for the experimental group (frames). Search objective and the search objective by frames interaction were not significant so we pooled across search objective and determined that the control and experimental group did not differ statistically in terms of quantity biological models generated (ANOVA $F_{1,10} = 0.39$, $P = 0.54$). Variation among teams in number of biological models produced was greater for the experimental (SD= 7.9) versus the control group (SD= 4.5) but not significantly different (Bartlett test, $P = 0.25$). There was no difference in the variety of proposed biological models, in terms of the number of biological kingdoms represented, between the control and experimental groups (2.2, SD= 0.75).

**Frames Cited**

Among teams in the experimental group, while the average number of frame citations for teams assigned to Search Objective 1 (22, SD= 5) was nearly twice as large as for teams assigned to Search Objective 2 (10, SD= 8.72), this difference was not
statistically significant (ANOVA, $F_{1,4} = 4.3, P > 0.108$) due to small sample size and large within group variance. Also, the number of frame citations among teams in the experimental group did not vary significantly as a function of the specific frame, assigned search objective, or the interaction (ANOVA, $F_{7,16} = 0.8243, P > 0.582$). However, the number of different frames used was significantly positively related to the total number of biological models generated ($r^2 = 0.81, P = 0.049$). Teams provided the four frames differed in the frequency that different frames were adopted to identify biological models ($\chi^2_{12,96} = 50.1, P < 0.001$).

**Influence of Demographics**

Participants’ perception about the difficulty of the exercise as reflected on a five point Likert scale (1= Very Difficult, 5= Very Easy) was not related to whether they were in the control or experimental group (3.3 vs. 3.1 respectively; ANOVA $F_{1,88} = 1.8, P = 0.18$). Moreover, demographic traits including age, educational attainment (possession of a college degree), and disciplinary background did not influence perceived difficulty, but gender did, with males (n=56) reporting having greater difficulty with the exercise than females (n=34) (3.4 vs. 3.0; ANOVA $F_{1,88} = 5.1, P = 0.03$) irrespective of whether they were in the control or experimental group. A participant’s prior familiarity with BID was not related to their perception of the difficulty of the exercise for either the control (P > 0.78) or the experimental group (P > 0.21).
Table 5.4. Summary of notable quantitative results.

<table>
<thead>
<tr>
<th>Effect</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average # biological models</td>
<td>17.8 models per team (frames) 15.5 models per team (no frames)</td>
</tr>
<tr>
<td>generated (quantity). Greater for</td>
<td>frames but not significantly different.</td>
</tr>
<tr>
<td>Within experimental group, average</td>
<td>22 citations (Search Objective 1) 10 citations (Search Objective 2)</td>
</tr>
<tr>
<td># frame citations. Greater for</td>
<td>Search Objective 1 but not significantly different.</td>
</tr>
<tr>
<td>Relationships</td>
<td>Description</td>
</tr>
<tr>
<td>Within experimental group, #</td>
<td>Positive effect: r² = 0.81, P = 0.049</td>
</tr>
<tr>
<td>different frames cited vs. #</td>
<td></td>
</tr>
<tr>
<td>biological models generated</td>
<td>Higher for men (3.4) vs. women (3.0): ANOVA F₁,₈₈ = 5.1, P = 0.03</td>
</tr>
</tbody>
</table>

Analysis / Discussion

Although, on average, teams provided frames identified a greater quantity of biological models, this difference was not statistically significant. The provision of frames also had no significant effect on variety of biological models in terms of number of biological kingdoms represented. The latter may be a direct result of the experimental context of a zoo. Zoos tend to highlight animal models over other types. Also, potential variety was inherently limited by the fact that participants were relying primarily on sight, which favors identification of macroscale physical attributes of animals, plants, and fungi over microscale physical or chemical attributes of protists, archaeabacteria, and eubacteria. Regardless, these results ran counter to our hypothesis that frames would increase the number and variety of biological models identified. It is important to note that power to test this hypothesis was low (10%). The low statistical power arose from a combination of a small effect of frames and high variance among
groups within treatments. Because there is very little pre-existing work, our inability to detect an effect of frames could stem from lack of a meaningful impact of frames, inadequate sample size, and/or other aspects of our experimental design and execution. In an emerging field like BID, our study is meaningful despite this negative result, because it serves as a substantive reference point for design of future studies. Variance among groups might be reduced in several ways to potentially lead to a clearer or stronger impact of frames. For example, high among group variance for teams given frames may have arisen because the effect of frames is complex. Our survey results, process coach observations, and comments made during the brief group discussion suggest that the provision of frames helps some R&D professionals search and identify a greater quantity of biological models, and impedes others, at least in the near term, as they spend time comprehending frames. Indeed, some participants said the frames helped them determine “what exhibits to visit and what to look for in those exhibits,” while others found the frames “confusing,” and “had to consume part of their allotted 60 minutes making sense of them.” One of the process coaches assigned to a team in the experimental group observed his team “taking a considerable amount of time to read instructions,” while another described an “initial struggle to understand the convergence frame, in particular.” One way to modify the design of our experiment would be to have participants in the experimental group exposed to the frames prior to the timed exercise, or receive in-advance training in how to use frames. Alternately, a follow-up study might investigate the effect of a single frame at a time to reduce comprehension challenges for participants assigned to the experimental group.
Anticipation of comprehensive complexity may be why texts that offer support for implementation of frames for search and identification of biological models present only one or two frames per publication (Baumeister, 2014; Werth & Shear, 2014; Yen et al., 2010).

Interestingly, the number of different frames used by teams in the experimental group was significantly positively related to the total number of biological models generated. The four frames provided to teams in the experimental group may be complimentary in that each led R&D professionals to different biological models. A set of complimentary frames compiled from the literature (Baumeister, 2014; Kennedy & Marting, 2016; Werth & Shear, 2014; Yen et al., 2010) and expanded upon could result in a significant positive effect of providing frames on the quantity of biological models generated. Survey 2, administered to individuals in the experimental group asked what other frames of inquiry (in addition to those provided) might support search and identification of biological models. Some of the responses provide basis for an expanded set of potentially complimentary frames:

1. “A frame that encourages consideration of how a species evolved over time; what features changed and in what way to advance a solution? What is the trajectory for future change?”

2. “A frame that encourages search for the exact opposite behavior (e.g. repulsion instead of adhesion)”

3. “A frame that considers opposition in nature - how do predators overcome evolved solutions?”
During the brief group discussion that followed the exercise, one participant expressed her opinion that “the frames of inquiry were unnecessary in a stimulus-rich environment like the zoo.” This participant added that “in a different context, like a stark conference room, the frames may have been more useful.” Echoing this sentiment, another participant suggested frames “would be more helpful to push a search for biological models further after all the obvious models have been identified.” Based on these comments, the value of frames for facilitating search and identification of analogous solutions in biology might depend on the richness of the search context or could be more beneficial, regardless of context, when introduced partway through a search after more obvious models have been identified.

Irrespective of whether they were in the control or experimental group, males perceived the BID exercise to be significantly more difficult than females. Educational studies have discovered negative correlations between perceived task difficulty and level of interest (Li, Lee, & Solmon, 2008; Tanaka & Murayama, 2014). It follows that female participants, who reported having significantly less difficulty with the BID exercise, may have been more interested by it. Supposing this is true, it would add to existing evidence that BID, an approach to environmentally sustainable product innovation (Kennedy & Marting, 2016; Lurie-Luke, 2014), attracts underrepresented female populations to STEM. Previous studies have found sustainability-themed design projects are disproportionately appealing to women (Oehlberg, Shelby, & Agogino, 2010; Zimmerman & Vanegas, 2007), and can increase women’s confidence in engineering problem-solving (Oehlberg et al., 2010). Women are drawn to programs
and initiatives that link science, technology, and engineering to real world applications, showing how engineering principles can be applied to solve problems, thereby improving people’s lives (Koppel, Cano, & Heyman, 2002). As an applied design science, BID emphasizes this link.

The goal of this field-based study was to answer the following question: In industry practice of BID, do frames of inquiry support search and identification of biological models? Our study did not find significant positive effects of frames on quantity or variety of biological models generated. It may be that there is, indeed, no effect of the experimental treatment. While the scale of our study was arguably large for the context in which we were working, it remains to be seen if further testing of the effectiveness of frames in a way that accounts for relatively small effect size and/or high variance is warranted. There are very few BID studies conducted in industrial settings even though the results of such studies might be more compelling to corporate R&D teams than studies conducted in academic settings with students. Indeed, our own anecdotal experience suggests that corporate R&D teams are interested in BID, but potentially discouraged from implementing it given the shortage of definitive industry-based studies elucidating best practices. Business professionals are an understudied population requiring research attention (Druckman & Kam, 2009). It is far more common to assess innovation techniques with student participants in a classroom setting (Kilgour & Koslow, 2009) because students, and undergraduates in particular, are readily accessible, abundant, and tend to be receptive to complex experimental designs (Bello et al., 2009). In many fields, results of experiments using
student participants are assumed to be generalizable (Druckman & Kam, 2009); but innovation is especially sensitive to the influence of context and life experience (Bello et al., 2009). In this field, experimental findings based on student behaviors in classroom settings are less likely to be generalizable for business application (Sears, 1986). Undergraduates are distinct from business professionals because, at an average 18-22 years old, they tend to lack crystallized attitudes (Henrich, Heine, & Norenzayan, 2010), have limited firsthand experience of corporate culture, and without domain expertise, are not privy to existing solutions. Collecting data in a corporate environment, through face-to-face conversation and behavioral observation, at the site where participants experience the phenomenon under study, lends credibility to findings (Creswell, 2007; Denzin and Lincoln, 2005; LeCompte and Schensul, 1999; Marshall and Rossman, 2011). So how do we design studies with business professionals that do generate statistically significant results and encourage widespread adoption of BID?

This study offers insight, by revealing that the industrial research context may require larger sample sizes and/or conditions which maximize potential effect sizes to ensure results are interpretable. These insights can contribute to how scholars and practitioners continue to pursue best practices for BID in contexts other than the classroom. A follow on to this study could double the sample size and reduce variance in the effect of frames by using a single search objective instead of two. A follow on

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5 Some of our study participants were undergraduates interning at the participating company during summer break, but by July 15, 2015, they were fully onboarded with at least two months’ experience with the company. They participated in this study in their capacity as interns (vs. students) in a real (vs. simulated) business environment.
might also reduce and refine the number of frames offered as a way of reducing variance in the effect of frames as compared to no frames. While authentic R&D sessions may not provide ideal platforms for maximizing sample size and controlling sources of variance while isolating a few experimental effects, we believe our results warrant further exploration. Studies in authentic business context could significantly advance both practice and theory in the emerging and rapidly expanding field of BID (Fermanian Business & Economic Institute, 2013).

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CHAPTER VI

EFFECT OF INDUSTRIAL VS. BIOLOGICAL ANALOGIES
ON CREATIVITY OF BUSINESS PROFESSIONALS

Under Review:


Abstract

The objective of this study was to test the effect of far-field industrial (i.e. man-made) vs. biological analogies on creativity of business professionals from two organizations engaged in the idea generation phase of new product development. Psychological effects as reflected in language use were measured via computerized text analysis of transcribed audio recordings of ideation sessions (tool: Linguistic Inquiry Word Count 2015). Effects on quality of product concepts generated by participants were measured via analysis of 15 judges’ multidimensional creativity ratings (tool: Consolidated Creative Solutions Diagnosis Scale). Though psychological effects were undetectable, our results suggest presenting new product development professionals with biological analogies as ideation stimulus increases novelty (P < 0.0001) and may increase elegance (P = 0.074) of solutions generated. Presenting far-field industrial analogies as ideation stimulus increases relevance and effectiveness (P = 0.025) of
solutions generated. This study serves as a source of evidence that biomimicry (design by analogy to biology) is an effective approach to product innovation. It also shows that there is an important role for far-field industrial analogies in stimulating ideas during new product development. A strategically designed brainstorming session should prime innovators with both far-field industrial and biological analogies to generate maximally creative ideas.

Introduction

Analogies are often used in idea generation to transfer knowledge through analogical mapping from a source domain (a domain of prior knowledge) to a target domain (the problem domain) (Gentner, 1983; Gentner & Forbus, 2011; Holyoak & Thagard, 1996; Linsey, Wood, & Markman, 2008; Mak & Shu, 2004). Analogies can drive innovative thought by enabling thinking across conceptual boundaries (Gentner et al., 1997; Gentner, Loewenstein, & Thompson, 2003; Holyoak & Thagard, 1996; Perkins, 1997; Polya, 1954; Roukes, 1988) especially when solving problems with a large solution space (Nijstad, Stroebe, & Lodewijks, 2002; Tseng, Moss, Cagan, & Kotovsky, 2008).

Analogies can be classified by the conceptual distance between the source and target domain as either near- or far-field (Dahl & Moreau, 2002). Near-field analogies come from source domains that significantly overlap in terms of surface-level attributes with the target domain (Dahl & Moreau, 2002). For example, faced with the problem of developing a more effective non-stick coating for cookware, an innovator might be inspired by the near-field analogy of non-stick ketchup or honey containers designed to
fully vacate a viscous food product. Near-field analogies can be useful, but are known to lead to form fixation, which reduces idea variety (Dahl & Moreau, 2002). Far-field analogies come from source domains with minimal overlap in terms of surface-level attributes, but structural similarity to the target domain (Dahl & Moreau, 2002). Faced with the same problem of developing a more effective non-stick coating for cookware, an innovator might be inspired by the far-field analogy of burn bandages designed for painless removal. Far-field analogies are widely considered to be more effective at driving innovation, since they serve as the basis for mental leaps (Gentner & Markman, 1997; Holyoak & Thagard, 1996; Poze, 1983; Ward, 1998). Studies show using far-field analogies as ideation stimulus can increase novelty of concepts generated vs. near-field or no analogies (Chan et al., 2011; I. Chiu & Shu, 2012; Dahl & Moreau, 2002).

Despite broad agreement that far-field analogies are more likely to engender insight during idea generation vs. near-field analogies, we are not aware of work that has compared different types of analogies within the far-field category. The objective of this study is to determine if there is a difference in effect between far-field industrial (i.e. man-made) vs. far-field biological analogies on creativity of business professionals engaged in the idea generation phase of new product development. It is not uncommon for new product development professionals to use far-field industrial analogies to spark ideas. The popular innovation practice of patent landscaping—analyzing pre-existing intellectual property in a technological field (Bubela et al., 2013; Soni, Tripathi, & Musyuni, 2013)—often produces far-field industrial analogies. A keyword search of the patent database for ‘non-stick coatings’ or ‘methods of anti-adhesion’ might uncover
the previous far-field example of a burn bandage designed for painless removal. It is much less common for new product development professionals to use biological analogies as stimulus during idea generation. Design by analogy to biology is termed biomimicry by some researchers (Goel, 2016). Biomimicry is an emerging field based on the idea that natural selection favors highly-adapted, resource-efficient survival strategies—strategies that can be abstracted to address technical challenges (Benyus, 2008). Biomimicry holds tremendous potential for delivering radical, environmentally sustainable product innovations (Lurie-Luke, 2014; Goel et al., 2015; Kennedy & Marting, 2016), but its practice is limited among business professionals.

Where biological analogies are inherently far-field, industrial analogies can be either near- or far-field. In a prior study, (Wilson et al., 2010) compared ideas generated by participants exposed to a near-field industrial vs. biological analogy before conceptual design of a portable, leg immobilization device. Exposure to the biological analogy resulted in a near-significant increase in novelty and significant increase in variety of product concepts generated vs. exposure to the industrial analogy. This result offers support for sourcing analogies from biology for use in idea generation; but leaves an important question unanswered. Would a difference in effect have been detected if the experimental design controlled for analogical distance by presenting a far-field industrial analogy, rather than a near-field industrial analogy?

Our controlled follow-on study compares the effects of far-field industrial analogies vs. (inherently far-field) biological analogies on creativity of business professionals engaged in the idea generation phase of new product development.
Effects are measured using a combination of linguistic data and multidimensional creativity ratings to reveal variability in psychological processes and output. This refines the experimental design and expands upon the analysis framework used by Wilson et al. (2010), which did not include speech analysis and measured only two dimensions of output creativity–novelty and variety. If results show a difference in effects of far-field industrial vs. biological analogies on select dimensions of creativity, it can inform strategic design of brainstorming sessions that prime innovators with the form of ideation stimulus most likely to lead to desired output characteristics. If data shows biological analogies have some desired effects, this study will serve as a source of evidence that biomimicry advances product innovation, helping to justify broader implementation of the approach by corporate R&D teams.

Hypotheses

_Hypotheses tested via linguistic data analysis_

Designed by Joy Paul Guilford in 1967, The Alternative Uses Test measures an individual’s creativity by asking him or her to think of as many uses as possible for a simple object, like a brick or a shoe or a paperclip, in a timed exercise (Guilford, 1967). A study by Kim, Lee, and Lee (2012) found that in stream of consciousness writings, college students who scored higher on the Alternative Uses Test used fewer words associated with future-oriented thinking (e.g. may, will, soon), which suggests reduced focus on the future in favor of focus on the here-and-now. They also employed fewer linguistic indicators of tentativeness (e.g. maybe, perhaps), which suggests they were
less hesitant (i.e. more confident). A number of case studies suggest biomimicry has a significant positive effect on creativity (Hacco & Shu, 2002; Ivey Chiu & Shu, 2007; Sarkar, Phaneendra, & Chakrabarti, 2008; Kennedy & Marting, 2016); consequently we hypothesized that:

\[ H1: \text{Compared to far-field industrial analogies, biological analogies amplify language trends associated with creativity, decreasing frequency of words indicating: 1) future-oriented thinking, and 2) tentativeness.} \]

Intrinsic motivation is the desire to perform an action because of interest, enjoyment, and satisfaction derived from the action itself rather than external rewards. The creativity literature suggests that intrinsic motivation increases creativity (Hennessey & Amabile, 2010b). Biomimicry may be intrinsically motivating because it provides an opportunity for businesspeople to integrate hobbies, like hiking or watching nature documentaries, into their work (Kennedy & Marting, 2016). Feelings associated with intrinsic motivation – interest, joy, and satisfaction – improve mood (Ryan & Deci, 2000), and, oftentimes, use of words associated with positive emotion (e.g. love, nice, sweet) (Tausczik & Pennebaker, 2010). Therefore, we hypothesized that:

\[ H2: \text{Compared to far-field industrial analogies, biological analogies amplify language trends associated with intrinsic motivation, increasing frequency of words indicating positive emotion.} \]

Fischer, McDonnell, and Orasanu (2007) found that higher performing groups use more assenting (e.g. agree, OK, yes) vs. dissenting responses, which indicate the group is behaving as a cohesive unit, acknowledging and elaborating on each other’s ideas. There is also evidence that groups with higher language-style matching (LSM)
scores are more tightly knit (Pennebaker, 2013). Biomimicry may build a sense of community and encourage group cohesion by increasing awareness of the interconnectedness and interdependence of living things, humans included (Biomimicry 3.8, 2016; Kennedy et al., 2015; Seebode et al., 2012). Therefore, we hypothesized that:

**H3:** Compared to far-field industrial analogies, biological analogies amplify language trends associated with group cohesion, increasing frequency of words indicating assent, as well as average language-style-matching scores.

According to Wang, Guidice, Tansky, & Wang (2010), an innovation-oriented culture values and promotes tolerance of uncertainty and risk-taking. Biomimicry may increase tolerance of uncertainty and risk-taking because examination of biological strategies nurtures an appreciation of adaptive evolution, a process which is highly unpredictable due to the dynamic natural environments in which it occurs (Natarajan et al., 2016). Business environments are also highly dynamic. A business professional who recognizes this similarity will be inclined to accept uncertainty as inevitable, and risk-taking as necessary and unavoidable. With this mindset, he or she is likely to use fewer expressions of certainty (e.g. always, never) and fewer linguistic indicators of risk evaluation (e.g. danger, concern, doubt). Therefore, we hypothesized that:

**H4:** Compared to far-field industrial analogies, biological analogies amplify language trends associated with an innovation-orientation, decreasing frequency of words indicating: 1) certainty and 2) risk evaluation.

**Hypotheses tested via analysis of creativity ratings**

The following hypotheses were formulated after we completed a creativity ratings factor analysis which extracted three dimensions potentially influenced by
analogy type. Results of the factor analysis are described in detail in Data Analysis under Methods.

In our previous work (Kennedy & Marting, 2016) comparing biomimicry vs. patent landscaping, we found that the biomimicry approach produced intellectual property that was more impressive in terms of technological novelty. Biological references may produce particularly novel ideas because biology solves problems differently than conventional technology (Vincent et al., 2006). In engineered systems, problems are solved through manipulation of energy more than 70% of the time, whereas in biological systems, problems are solved this way less than 5% of the time. Biological systems tend to leverage information transfer and structure, rather than energy, to solve problems (Bogatyrev & Bogatyreva, 2009a; McKeag, 2013). Biological analogies may thus offer a fundamentally new perspective on how to solve a problem, prompting a radically new approach. Therefore, it was hypothesized that:

H5: Compared to far-field industrial analogies, biological analogies increase Novelty of product concepts generated.

Janine Benyus wrote on the practice of biomimicry, “When we stare this deeply into nature's eyes, it takes our breath away, and in a good way, it bursts our bubble. We realize that all our inventions have already appeared in nature in a more elegant form and at a lot less cost to the planet” (Benyus, 2008). An elegant solution strikes the beholder as beautiful (Cropley & Kaufman, 2012). According to the biophilia hypothesis, solutions that emulate biological forms are perceived as particularly beautiful because humans have an innate, positive emotional response to forms that mimic naturally
occurring geometries, patterns, colors, and textures (van Vliet, 2015; Wilson, 1984). An
elegant solution also impresses in terms of polish. It is seen as neat and refined, stripped
of unnecessary elements (Cropley & Kaufman, 2012). Compared to industrial solutions,
biological solutions are pared down. They tend to be constructed of fewer components,
and do more with less (Ulhøi, 2015). Therefore, we hypothesized that:

\[ H6: \text{Compared to far-field industrial analogies, biological analogies increase}
\text{Elegance of product concepts generated.} \]

A relevant and effective solution satisfies task specifications and fulfills a
practical purpose (Cropley & Cropley, 2010). A relevant and effective solution is
incremental, in that it reflects conventional knowledge and extends existing lines of
thought (Cropley & Kaufman, 2012; Cropley, Kaufman, & Cropley, 2011). A case study
comparing biomimicry to patent landscaping found the biomimicry approach produced
radical solutions whereas the patent landscaping approach produced more incremental
solutions (E. Kennedy & Marting, 2016). Therefore, we hypothesized that:

\[ H7: \text{Compared to far-field industrial analogies, biological analogies decrease}
\text{Relevance & Effectiveness of product concepts generated.} \]

Methods

Participants and Research Setting

The sample consisted of 24 new product development professionals (19 men
and 5 women) from two organizations, a manufacturer of skin health and hygiene
solutions (Company A), and a product design firm (Company B). Of the participants,
16.7% were in the age group of 20-29, 41.7% in the age group of 30–39, 25% in the age group of 40–49, 12.5% in the age group of 50-59, and 4.2% in the age group 60-69. For education, 33.3% had a Master’s or higher degree, 62.5% had a Bachelor’s degree, and 4.2% chose not to give an answer for this demographic. Participants were recruited by project managers at their respective organizations to attend a two-hour idea generation session, an activity considered within the scope of regular job duties with no extra compensation. Idea generation sessions took place in conference rooms at company office locations during normal business hours.

**Analogical Stimulus**

*Far-Field Industrial Analogies.* The project manager from Company A and the project manager from Company B each identified one dozen far-field industrial analogies relevant to their organization’s innovation objective. Identification methods included recall and internet research (including patent landscaping). A sample of far-field industrial analogies is provided in Figure 6.1.
Figure 6.1. Far-field industrial analogies. Sample far-field industrial analogies provided to participants generating concepts for easily and intuitively transferable dispenser brackets for 450 mL hand sanitizer dispensers (A) and participants generating concepts for universal, full motion wall mounts for flat-panel TVs (B).

**Biological Analogies.** The lead author of this study identified one dozen biological analogies relevant to Company A’s innovation objective and one dozen biological analogies relevant to the Company B’s innovation objective. Identification methods included keyword searches of biological databases and immersion in a natural environment. A sample of biological analogies is provided in Figure 6.2.
Figure 6.2. Biological analogies. Sample biological analogies provided to participants generating concepts for easily and intuitively transferable dispenser brackets for 450 mL hand sanitizer dispensers (A) and participants generating concepts for universal, full motion wall mounts for flat-panel TVs (B).

Experimental Procedure

Upon arrival to the conference room, the 12 new product development professionals from Company A were given a general introduction explaining that they would be participating in a structured brainstorming session. They were informed of the innovation objective:

Generate concepts for easily and intuitively transferable dispenser brackets for 450 mL hand sanitizer dispensers. These dispenser brackets are for use in healthcare settings and should be able to firmly grip hospital beds, IV poles,
service carts, etc. without damaging surfaces. Preferred solutions will minimize material, complexity, and cost to manufacture.

Next, participants were randomly assigned to one of four teams of three. The project manager presented a dozen far-field industrial analogies. Participants were given 20 minutes to ideate in three-person teams using the far-field industrial analogies as stimulus. They were provided paper and pencil and instructed to document and numerically label distinct solutions. Participants were audio-recorded for this 20-minute period and repeatedly encouraged throughout the activity to verbalize their thought processes. After 20 minutes elapsed, audio-recorders were turned off and marked paper was collected and replenished.

Following a 10-minute break, the lead author of this study presented a dozen biological analogies. Participants were given another 20 minutes to ideate in the same three-person teams using the biological analogies as stimulus. No new instructions were given. Participants were audio-recorded as before. After 20 minutes elapsed, audio-recorders were turned off and marked paper was collected.

The same procedure was followed with the 12 new product development professionals from Company B, the only difference being the innovation objective:

Generate concepts for universal, full motion wall mounts for flat-panel TVs. Preferred solutions will be easy to install with minimal wall damage, have a 150-lb weight capacity, and be height-adjustable. Ideally, solutions will be compatible with ultra-slim, curved, flexible, bezel-less TVs (market trends).

Audio recordings were transcribed and rate-able output was extracted from solutions documented by participants. A solution was deemed rate-able if it included a
sketch and an intelligible description (written and/or verbal) which formed the basis for annotation. A total of 63 solutions were deemed rate-able, 19 product concepts for easily and intuitively transferable dispenser brackets and 44 product concepts for universal, full motion wall mounts for flat-panel TVs. Annotation of rate-able concepts eliminated non-essential detail, redundancy, and replaced brand names with generic terms. An example rate-able concept is provided in Figure 6.3.

Figure 6.3. Example rate-able concept. This is the format (sketch and annotation) in which concepts were presented to raters.

Due to logistical constraints of our professional business setting, we were not able to randomize presentation order of analogy type to groups. There is a body of work which suggests that the quantity and variety of ideas contributed during brainstorming rapidly declines over time (Kohn & Smith, 2011; Wang & Rosé, 2007), and that shorter brainstorming sessions are more productive than longer ones (Coyne & Coyne, 2011; McClure, 2014). Consequently, we chose to present product development professionals with far-field industrial analogies before biological analogies with the rationale that it would serve as a conservative test of our hypotheses.
Measures

Linguistic data. Audio transcriptions were analyzed using Linguistic Inquiry Word Count (LIWC) 2015 software. LIWC, originally developed by James W. Pennebaker, Martha E. Francis, and Roger J. Booth, takes text as input and counts the percentage of words that reflect different emotions, thinking styles, and social concerns (Francis & Pennebaker, 1993; Pennebaker, Francis, & Booth, 2001). The LIWC2015 development manual was co-authored by James W. Pennebaker, Ryan L. Boyd, Kayla Jordan, and Kate Blackburn (Pennebaker et al., 2015).

Creativity ratings. Study authors recruited 15 University of Akron employees to evaluate the creativity of 63 rate-able product concepts generated by participants. Raters using the 22-item Consolidated Creative Solutions Diagnosis Scale (C-CSDS) developed by David H. Cropley, James C. Kaufman, and Arthur J. Cropley (Cropley et al., 2011; Cropley & Kaufman, 2012) (Appendix 1). The C-CSDS is an empirically-validated instrument for measuring the functional creativity of product concepts across five categories (Relevance & Effectiveness; Problematization; Propulsion; Elegance; Genesis) using domain expert and/or non-expert judges (Cropley & Kaufman, 2012; Cropley et al., 2011). Functional creativity is creativity that leads to practically useful rather than merely aesthetic output (Cropley & Cropley, 2008). The C-CSDS is preferred to the well-known Consensual Assessment Technique (CAT) (Amabile, 1983, 1996; Kaufman, Plucker, & Baer, 2008) for three reasons. First, it does not require domain

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6 As University of Akron employees, raters were bound by nondisclosure agreements between participating companies and the University, and kept design concepts strictly confidential.
expert judges, which can be expensive and difficult to obtain (Cropley et al., 2011). Second, it acknowledges multiple dimensions of creativity to provide a differentiated, rather than a blanket assessment of rated material (Cropley et al., 2011; Haller, Courvoisier, & Cropley, 2011). Third, judgments using the C-CSDS are completed faster than judgements using the CAT (Besemer & O’Quin, 1999; E. L. Mann, 2009).

Raters were provided a link to a survey built using Qualtrics software (Qualtrics LLC, Provo, UT) and hosted online. The four-hour survey presented the 63 rate-able product concepts (sketch and annotation) and associated innovation objective in random order. Raters, blind to condition, determined the extent to which 22 creativity indicators applied to each product concept using a 5-point Likert scale (1 = Not at all, 5 = Very much). As a check, they also rated overall creativity of the product concept on the same scale (“Indicate how creative, overall, the output is”). Survey progress auto-saved and raters were not required to answer all questions in a single sitting.

Data Analysis

Linguistic data. Linguistic data were used to test Hypotheses 1-4 (Table 6.1). Repeated measures Multivariate Analysis of Variance (MANOVA) was used to estimate between (‘organization’) and within (‘analogy’ and ‘analogy * organization’) subject effects on language trends. Independent variables were coded as categorical. Analogy type had two levels (biological and far-field industrial) and organization had two levels (Company A and Company B). Homogeneity of variances and normality of the residuals
were verified to meet assumptions of parametric statistics. Statistics were performed using JMP® Pro 12 (SAS Institute, Cary, NC).

Table 6.1. Hypotheses tested via analysis of linguistic data.

<table>
<thead>
<tr>
<th>Hypothesis</th>
<th>Dependent variable</th>
<th>Associated LIWC2015 Category / Predicted Trend</th>
</tr>
</thead>
<tbody>
<tr>
<td>1: Biological analogies amplify language trends associated with creativity vs. far-field industrial analogies.</td>
<td>Words indicating future-oriented thinking</td>
<td>FocusFuture / (-)</td>
</tr>
<tr>
<td></td>
<td>Words indicating tentativeness</td>
<td>Tentat / (-)</td>
</tr>
<tr>
<td>2: Biological analogies amplify language trends associated with intrinsic motivation vs. far-field industrial analogies.</td>
<td>Words indicating positive emotion</td>
<td>Posemo / (+)</td>
</tr>
<tr>
<td>3: Biological analogies amplify language trends associated with group cohesion vs. far-field industrial analogies.</td>
<td>Group member language-style matching (LSM) scores*</td>
<td>Assent / (+)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ppron / (+)</td>
</tr>
<tr>
<td>4: Biological analogies amplify language trends associated with an innovation-orientation vs. far-field industrial analogies.</td>
<td>Words indicating certainty</td>
<td>Certain / (-)</td>
</tr>
<tr>
<td></td>
<td>Words indicating risk evaluation</td>
<td>Risk / (-)</td>
</tr>
</tbody>
</table>

*LSM score = 1 - \(\frac{1}{2}\)\(\text{Person 1 \%Ppron - Person 2 \%Ppron}\). In this study, LSM score = average of two LSM scores between study participant and his or her two group members.

Creativity ratings. The C-CSDS (Appendix B) is designed to measure creativity of product concepts across five categories (Cropley, Kaufman, & Cropley, 2011; Cropley & Kaufman, 2012):

1. Relevance & Effectiveness – The output is fit for purpose.
2. Problematization – The output helps to define the problem/task at hand.
4. Elegance – The output is well-executed.
5. Genesis – The output changes how the problem/task is understood.

In our study a factor analysis (Oblimin rotation; see Haller et al., 2011) extracted three dimensions: Novelty (corresponding to Propulsion and Genesis), Elegance, and Relevance & Effectiveness (Table 6.2).
Table 6.2. Factor analysis loadings. The first three factors were retained with eigenvalues ≥ 1.

<table>
<thead>
<tr>
<th>C-CSDS Category</th>
<th>C-CSDS Creativity Indicator</th>
<th>Factor 1: Novelty</th>
<th>Factor 2: Elegance</th>
<th>Factor 3: Relevance &amp; Effectiveness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relevance &amp; Effectiveness</td>
<td>Correctness</td>
<td>-0.103</td>
<td>-0.010</td>
<td>0.926</td>
</tr>
<tr>
<td></td>
<td>Performance</td>
<td>0.075</td>
<td>0.027</td>
<td>0.862</td>
</tr>
<tr>
<td></td>
<td>Appropriateness</td>
<td>0.107</td>
<td>0.062</td>
<td>0.789</td>
</tr>
<tr>
<td>Problematization</td>
<td>Diagnosis</td>
<td>0.553</td>
<td>0.151</td>
<td>0.301</td>
</tr>
<tr>
<td></td>
<td>Prescription</td>
<td>0.586</td>
<td>0.146</td>
<td>0.307</td>
</tr>
<tr>
<td></td>
<td>Prognosis</td>
<td>0.544</td>
<td>0.135</td>
<td>0.324</td>
</tr>
<tr>
<td>Propulsion</td>
<td>Direction</td>
<td>0.803</td>
<td>-0.027</td>
<td>0.173</td>
</tr>
<tr>
<td></td>
<td>Reinitiation</td>
<td>0.902</td>
<td>0.039</td>
<td>-0.107</td>
</tr>
<tr>
<td></td>
<td>Redefinition</td>
<td>0.865</td>
<td>0.057</td>
<td>-0.008</td>
</tr>
<tr>
<td></td>
<td>Generation</td>
<td>0.890</td>
<td>0.098</td>
<td>-0.097</td>
</tr>
<tr>
<td>Elegance</td>
<td>Convincingness</td>
<td>0.092</td>
<td>0.782</td>
<td>0.149</td>
</tr>
<tr>
<td></td>
<td>Pleasingness</td>
<td>0.081</td>
<td>0.915</td>
<td>-0.049</td>
</tr>
<tr>
<td></td>
<td>Completeness</td>
<td>-0.072</td>
<td>0.960</td>
<td>0.054</td>
</tr>
<tr>
<td></td>
<td>Gracefulness</td>
<td>-0.038</td>
<td>0.995</td>
<td>-0.029</td>
</tr>
<tr>
<td></td>
<td>Harmoniousness</td>
<td>0.016</td>
<td>0.949</td>
<td>-0.035</td>
</tr>
<tr>
<td></td>
<td>Sustainability</td>
<td>0.376</td>
<td>0.244</td>
<td>0.036</td>
</tr>
<tr>
<td>Genesis</td>
<td>Foundationality</td>
<td>0.953</td>
<td>-0.106</td>
<td>0.018</td>
</tr>
<tr>
<td></td>
<td>Transferability</td>
<td>0.869</td>
<td>-0.101</td>
<td>0.027</td>
</tr>
<tr>
<td></td>
<td>Germinality</td>
<td>0.907</td>
<td>0.020</td>
<td>-0.039</td>
</tr>
<tr>
<td></td>
<td>Seminality</td>
<td>0.800</td>
<td>0.064</td>
<td>0.053</td>
</tr>
<tr>
<td></td>
<td>Vision</td>
<td>0.875</td>
<td>0.038</td>
<td>-0.017</td>
</tr>
<tr>
<td></td>
<td>Pathfinding</td>
<td>0.951</td>
<td>-0.033</td>
<td>-0.072</td>
</tr>
</tbody>
</table>

Factor loadings showed respondents treated all indicators categorized under what the C-CSDS calls Propulsion and Genesis (Cropley et al., 2011; Cropley & Kaufman, 2012) as involving a single dimension of judgment. What these categories have in common is they both relate to novelty. High scores in the Propulsion category suggest a solution that is *original*; one that offers a fundamentally *new* perspective on the problem/task at hand (situational novelty) (Cropley & Kaufman, 2012). High scores in the Genesis category indicate a solution that suggests a *novel* basis for future work; one which goes beyond the problem/task as hand, helping to conceptualize a broader range of issues in a *new* way (generative novelty) (Cropley & Kaufman, 2012; Cropley et al., 2011). The fact that Propulsion and Genesis loaded onto the same factor is not surprising. A previous study found a strong correlation between Propulsion and Genesis (Cropley & Kaufman, 2012). Factor 1, titled ‘Novelty,’ explained 43% variance...
Similarly, respondents treated five of six indicators categorized under what the C-CSDS calls Elegance (Cropley et al., 2011; Cropley & Kaufman, 2012) as belonging together. The only Elegance indicator that did not load to this factor was Sustainability. A solution receiving high scores in the Elegance category strikes raters as beautiful, refined, and harmonious (Cropley & Kaufman, 2012). Factor 2, titled ‘Elegance,’ explained 34% variance in ratings, and had a moderately strong, positive correlation with overall creativity ratings (R = 0.604).

Finally, respondents treated all indicators categorized under what the C-CSDS calls Relevance & Effectiveness (Cropley et al., 2011; Cropley & Kaufman, 2012), as a unified dimension. A solution receiving high scores in the Relevance & Effectiveness category leverages conventional knowledge to satisfy the problem statement (Cropley & Kaufman, 2012). High scores in Relevance & Effectiveness denote a solution that is routine (i.e. incremental), in that it extends existing lines of thought (Cropley et al., 2011). Factor 3, which maps exactly with C-CSDS Relevance & Effectiveness indicators, was titled ‘Relevance & Effectiveness.’ Factor 3 explained 23% variance in ratings, and had a weak, positive correlation with overall creativity ratings (R = 0.444).

Hypotheses 5-7 were generated based on results of this factor analysis, which extracted three distinct dimensions potentially influenced by analogy type. Creativity ratings were used to test Hypotheses 5-7. ANOVAs were performed on factor scores to estimate the main effects of analogy type, individual rater, organization, and the
interaction between individual rater and organization, on creativity of product concepts. Independent variables were coded as categorical. Analogy type had two levels (biological and far-field industrial), individual rater had 15 levels (15 total raters) and organization had two levels (Company A and Company B). Models of full rank were run first, followed by removal of non-significant interaction terms leaving the reduced models interpreted in the results below. Homogeneity of variances and normality of the residuals were verified to meet assumptions of ANOVA. Statistics were performed using JMP® Pro 12.

Results

Linguistic data

This section presents results associated with analysis of linguistic data. Values are reported as a mean followed by its 95% confidence interval [lower limit, upper limit]. All values are back transformed to the original measurement scale (percentage).

H1: Compared to far-field industrial analogies, biological analogies amplify language trends associated with creativity, decreasing frequency of words indicating: 1) future-oriented thinking, and 2) tentativeness.

Compared to far-field industrial analogies (FI), biological analogies (B) do not significantly affect frequency of words indicating future-oriented thinking (0.967 [0.730, 1.238] vs. 1.124 [0.900, 1.373]) [FI vs. B, respectively]; MANOVA F₁, 22 = 1.695, P = 0.206) or words indicating tentativeness (4.303 [3.898, 4.727] vs. 3.844 [3.372, 4.345]) [FI vs. B, respectively]; MANOVA F₁, 22 = 4.067, P = 0.056), but the latter difference is near-significant, with biological analogies reducing frequency of words indicating
tentativeness. This is true across organizations; the analogy type by organization interaction is not significant for either parameter, words associated with future-oriented thinking ($P = 0.784$) or words associated with tentativeness ($P = 0.520$).

**H2:** Compared to far-field industrial analogies, biological analogies amplify language trends associated with intrinsic motivation, increasing frequency of words indicating positive emotion.

Overall, biological analogies do not significantly increase frequency of words indicating positive emotion compared to far-field industrial analogies ($1.533 [1.291, 1.795]$ vs. $1.757 [1.451, 2.093]$) [FI vs. B, respectively]; MANOVA $F_{1, 22} = 1.884$, $P = 0.184$); however, the analogy type by organization interaction is significant. Compared to far-field industrial analogies, biological analogies seem to increase frequency of words indicating positive emotion among Company A participants ($1.346 [1.038, 1.693]$ vs. $2.127 [1.630, 2.689]$) [FI vs. B, respectively]; MANOVA $F_{1, 22} = 10.886$, $P = 0.003$) but the response for Company B participants seems relatively flat ($1.731 [1.387, 2.113]$ vs. $1.422 [1.142, 1.734]$) [FI vs. B, respectively]).

**H3:** Compared to far-field industrial analogies, biological analogies amplify language trends associated with group cohesion, increasing frequency of words indicating assent, as well as average language-style-matching scores.

Compared to far-field industrial analogies, biological analogies significantly increase frequency of words indicating assent ($0.675 [0.478, 0.906]$ vs. $1.122 [0.912, 1.352]$) [FI vs. B, respectively]; MANOVA $F_{1,22} = 17.405$, $P = 0.0004$), but do not significantly affect average language-style matching scores ($0.951 \pm 0.068$ vs. $0.961 \pm 0.044$ [FI vs. B, respectively]; MANOVA $F_{1,22} = 1.709$, $P = 0.205$). This is true across organizations; the analogy type by organization interaction is not significant for either
parameter: words indicating assent ($P = 0.126$) or average language-style matching scores ($P = 0.163$).

*H4: Compared to far-field industrial analogies, biological analogies amplify language trends associated with an innovation-orientation, decreasing frequency of words indicating: 1) certainty and 2) risk evaluation.*

Compared to far-field industrial analogies, biological analogies do not significantly affect frequency of words indicating certainty ($0.651 [0.543, 0.769]$ vs. $0.626 [0.436, 0.851]$) [FI vs. B, respectively]; MANOVA $F_{1,22} = 0.048, P = 0.829$) but do significantly decrease frequency of words indicating risk evaluation ($0.156 [0.069, 0.277]$ vs. $0.050 [0.013, 0.111]$) [FI vs. B, respectively]; MANOVA $F_{1,22} = 4.460, P = 0.046$). This is true across organizations; the analogy type by organization interaction is not significant for either parameter: words indicating certainty ($P = 0.855$) or words indicating risk evaluation ($P = 0.172$). The significant effect of analogy type on frequency of words indicating risk evaluation should be interpreted cautiously, as it is primarily driven by particularly infrequent use of words in the LIWC2015 Risk category among Company A participants receiving biological analogies ($0.015 [7E-5, 0.066]$ vs. $0.105 [0.027, 0.232]$) [Risk value for B among Company A vs. Company B participants, respectively].

*Creativity ratings*

This section presents results associated with analysis of creativity ratings. Inter-rater reliability of overall data is exceptionally high (Cronbach’s $\alpha = 0.969$). This alpha is well above 0.7, a generally accepted minimum (Kline, 2000). It falls in the Excellent range ($\alpha \geq 0.9$).
H5: Compared to far-field industrial analogies, biological analogies increase Novelty of product concepts generated (Factor 1).

An ANOVA shows significant effects of analogy type (P < 0.0001), individual rater (P < 0.0001), organization (P < 0.0001) and the interaction between individual rater and organization (P = 0.004), on Novelty of product concepts generated (Table 6.3). Compared to far-field industrial analogies, biological analogies significantly increase Novelty of product concepts generated (-0.048 ± 0.040 vs. 0.191 ± 0.038 [FI vs. B, respectively]). In general, raters gave product concepts generated by Company A participants higher Novelty scores (0.256 ± 0.048) than product concepts generated by Company B participants (-0.113 ± 0.032); however, this was not true across the board; there was a significant interaction between rater and company. Two of fifteen raters gave product concepts generated by Company B participants higher Novelty ratings.

Table 6.3. ANOVA, effects on Novelty of product concepts generated.

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>SS</th>
<th>F Ratio</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analogy Type</td>
<td>1</td>
<td>13.479</td>
<td>20.241</td>
<td>&lt; 0.0001*</td>
</tr>
<tr>
<td>Individual Rater</td>
<td>14</td>
<td>234.776</td>
<td>25.183</td>
<td>&lt; 0.0001*</td>
</tr>
<tr>
<td>Organization</td>
<td>1</td>
<td>27.205</td>
<td>40.853</td>
<td>&lt; 0.0001*</td>
</tr>
<tr>
<td>Individual Rater x Organization</td>
<td>14</td>
<td>21.599</td>
<td>2.317</td>
<td>0.004*</td>
</tr>
<tr>
<td>Pure Error</td>
<td>885</td>
<td>591.3</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*significant effect

H6: Compared to far-field industrial analogies, biological analogies increase Elegance of product concepts generated (Factor 2).

An ANOVA shows significant effects of individual rater (P < 0.0001), organization (P < 0.0001) and the interaction between individual rater x organization (P = 0.002), on Elegance of product concepts generated (Table 6.4). The effect of analogy type is near significant (P = 0.074). Compared to far-field industrial analogies, biological analogies
tend to increase Elegance of product concepts generated (0.009 ± 0.038 vs. 0.100 ± 0.037 [FI vs. B, respectively]). Most raters (n = 10) gave product concepts generated by Company A participants higher Elegance scores (0.194 ± 0.046) than product concepts generated by Company B participants (-0.085= ± 0.030); however, this was not true across the board. Three of fifteen raters gave product concepts generated by Company A and Company B participants near-equal Elegance ratings; and two of fifteen gave product concepts generated by Company B participants higher Elegance ratings. The same two raters who diverged from the norm of giving product concepts generated by Company A participants higher Novelty Ratings, were included in this group of five raters associated with Elegance ratings.

Table 6.4. ANOVA, effects on Elegance of product concepts generated.

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>SS</th>
<th>F Ratio</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analogy Type</td>
<td>1</td>
<td>1.964</td>
<td>3.199</td>
<td>0.074</td>
</tr>
<tr>
<td>Individual Rater</td>
<td>14</td>
<td>283.650</td>
<td>33.004</td>
<td>&lt; 0.0001*</td>
</tr>
<tr>
<td>Organization</td>
<td>1</td>
<td>15.441</td>
<td>25.153</td>
<td>&lt; 0.0001*</td>
</tr>
<tr>
<td>Individual Rater x Organization</td>
<td>14</td>
<td>21.135</td>
<td>2.459</td>
<td>0.002*</td>
</tr>
<tr>
<td>Pure Error</td>
<td>885</td>
<td>591.3</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*significant effect

H7: Compared to far-field industrial analogies, biological analogies decrease Relevance & Effectiveness of product concepts generated (Factor 3).

An ANOVA shows significant effects of analogy type (P = 0.025), individual rater (P < 0.0001), and organization (P < 0.0001) on Relevance & Effectiveness of product concepts generated (Table 6.5). Compared to far-field industrial analogies, biological analogies decrease Relevance & Effectiveness of product concepts generated (0.112 ± 0.039 vs. -0.004 ± 0.038 [FI vs. B, respectively]). In general, raters gave product concepts
generated by Company A participants higher Relevance & Effectiveness scores (0.188 ± 0.047) than product concepts generated by Company B participants (-0.080 = ± 0.031). We report differences in factor scores across organizations because they could provide insight into generalizability of results across organizations/industries. These differences should not be interpreted as a reflection on relative creative ability. Creativity is highly context-dependent and can be impacted by everything from the nature of the task to the time of day that a brainstorming session is held.

Table 6.5. ANOVA, effects on Relevance & Effectiveness of product concepts generated.

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>SS</th>
<th>F Ratio</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analogy Type</td>
<td>1</td>
<td>3.223</td>
<td>5.039</td>
<td>0.025*</td>
</tr>
<tr>
<td>Individual Rater</td>
<td>14</td>
<td>264.095</td>
<td>29.497</td>
<td>&lt; 0.0001*</td>
</tr>
<tr>
<td>Organization</td>
<td>1</td>
<td>14.241</td>
<td>22.269</td>
<td>&lt; 0.0001*</td>
</tr>
<tr>
<td>Individual Rater x Organization</td>
<td>14</td>
<td>11.621</td>
<td>1.298</td>
<td>0.202</td>
</tr>
<tr>
<td>Pure Error</td>
<td>885</td>
<td>591.3</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*significant effect

Discussion

Interestingly, our findings offer support for all hypotheses tested via analysis of creativity ratings and non-support for all hypotheses tested via analysis of linguistic data (Table 6.6). The reason our data did not support any of the hypotheses tested linguistic data analysis could be because: 1) LIWC2015 is not suited for evaluating psychological effects in a business context; or 2) LIWC2015 is an appropriate analysis tool for this context, but for our sample, there were genuinely no psychological effects across experimental conditions (or at least none anticipated by our hypotheses). We explore both possibilities in sequence.
Table 6.6. Summary of hypotheses tests.

<table>
<thead>
<tr>
<th>Hypothesis</th>
<th>Data Type</th>
<th>Support / Non-support</th>
</tr>
</thead>
<tbody>
<tr>
<td>1: Compared to far-field industrial analogies, biological analogies amplify language trends associated with creativity, decreasing frequency of words indicating: 1) future-oriented thinking, and 2) tentativeness.</td>
<td>Linguistic</td>
<td>Non-support overall, but biological analogies result in a near-significant decrease in frequency of words indicating tentativeness (P = 0.056)</td>
</tr>
<tr>
<td>2: Compared to far-field industrial analogies, biological analogies amplify language trends associated with intrinsic motivation, increasing frequency of words indicating positive emotion.</td>
<td>Linguistic</td>
<td>Non-support overall, but significant analogy type by organization interaction; Biological analogies significantly increase frequency of words indicating positive emotion among Company A participants (P = 0.003)</td>
</tr>
<tr>
<td>3: Compared to far-field industrial analogies, biological analogies amplify language trends associated with group cohesion, increasing frequency of words indicating assent, as well as average language-style-matching scores.</td>
<td>Linguistic</td>
<td>Non-support overall, but biological analogies significantly increase frequency of words indicating assent (P = 0.0004)</td>
</tr>
<tr>
<td>4: Compared to far-field industrial analogies, biological analogies amplify language trends associated with an innovation-orientation, decreasing frequency of words indicating: 1) certainty and 2) risk evaluation.</td>
<td>Linguistic</td>
<td>Non-support overall, but biological analogies result in significant decrease in words indicating risk evaluation (P = 0.046); however, this is primarily driven by infrequent use of Risk words among Company A participants receiving biological analogies</td>
</tr>
<tr>
<td>5: Compared to far-field industrial analogies, biological analogies increase Novelty of product concepts generated.</td>
<td>Creativity ratings</td>
<td>Support (P &lt; 0.0001)</td>
</tr>
<tr>
<td>6: Compared to far-field industrial analogies, biological analogies increase Elegance of product concepts generated.</td>
<td>Creativity ratings</td>
<td>Semi-support (near-significant) (P = 0.074)</td>
</tr>
<tr>
<td>7: Compared to far-field industrial analogies, biological analogies decrease Relevance &amp; Effectiveness of product concepts generated.</td>
<td>Creativity ratings</td>
<td>Support (P = 0.025)</td>
</tr>
</tbody>
</table>

Complexity of language implies that computerized text analysis methods are imperfect (Grimmer & Stewart, 2013). Programs such as LIWC2015 ignore context, irony, sarcasm, and idioms (Tausczik & Pennebaker, 2010). More importantly, LIWC2015 was developed based on findings of research studies that were primarily conducted with college students in classroom settings (Tausczik & Pennebaker, 2010). These findings may not hold for business professionals (vs. college students) in a real (vs. contrived) environment, because word use is highly contextual (Grimmer & Stewart, 2013; Tausczik & Pennebaker, 2010). As such, LIWC2015 may not be suited for evaluating psychological effects in a business context.
We think it is more likely that LIWC2015 is suited for evaluating psychological effects in a business context, because while hypotheses testing using this analysis tool were not supported, we did detect significant differences across experimental conditions for word use rate in certain LIWC2015 categories. What follows is a discussion of those results that assumes validity of the tool in the context of this study.

Though H2 was not supported overall, compared to far-field industrial analogies, biological analogies did significantly increase frequency of words indicating positive emotion among Company A participants (P = 0.003), a language trend associated with intrinsic motivation (Ryan & Deci, 2000; Tausczik & Pennebaker, 2010). Organizational psychologists have found that each workplace develops its own group emotion which over time creates shared emotion norms that are proliferated and reinforced by the behavior of employees. (Kelly & Barsade, 2001). Emotion norms are more readily transferred via face-to-face vs. remote interaction, because face-to-face interaction involves non-verbal cues that convey mood (Belkin, 2009); so some argue small work forces with more localized operations will develop stronger emotion norms (Hahn, 2007). Company A is larger, with more geographically distributed operations vs. Company B. It is possible that with fewer employees and more localized operations, Company B has a more pervasive workplace emotion norm, making employees less susceptible to a change in emotion in response to a very temporary (20-min duration) experimental condition. A longitudinal study or a cross-sectional study designed to expose participants to the experimental condition for a longer period may have resulted
in overall support for H2. Alternately, biomimicry may only serve to bolster intrinsic motivation in companies of a certain size or cultural malleability.

Though H3 was not supported overall, compared to far-field industrial analogies, biological analogies did significantly increase frequency of words indicating assent (P = 0.0004), a language trend that has been associated with group cohesion (Fischer et al., 2007). It is our interpretation that in this case, the significant increase in assent words indicates something other than group cohesion, because LSM scores, another indicator of group cohesion (Pennebaker, 2013), remained constant across experimental conditions. It is possible that the significant increase in assent words among groups receiving biological analogies is a reflection of greater conversational involvement (Nguyen & Fussell, 2014), and therefore, interest (Nguyen & Fussell, 2015). Interest increases cognitive functioning and persistence (Hidi, 2001). Thus, while H3 was not supported overall, the significant increase in words indicating assent associated with biological analogies warrants further investigation, especially in relation to H2, since interest is a precursor for intrinsic motivation (Hennessey & Amabile, 2010b).

Now we transition to discussion of results associated with analysis of creativity ratings. According to Guadagnoli & Velicer (1988), if a minimum of four variables (loading on the same factor) show loadings above 0.60, factor structures are likely to be robust enough to generalize independently of sample size. Our creativity ratings factor structure, involving three dimensions (Novelty, Elegance, and Relevance & Effectiveness) meets this condition for generalizability.
As explained in Methods, the logistical constraints of our professional business setting prevented us from randomizing presentation order of analogy type to groups. Order effect could thus be perceived as a confounding variable, but we are confident that presenting participants with far-field industrial analogies before biological analogies disadvantages biological analogies for a conservative test of our hypotheses, most of which predict positive effects of biological analogies. This is because literature on brainstorming contends quantity and variety of ideas rapidly declines over time (Kohn & Smith, 2011; Wang & Rosé, 2007), and shorter sessions are more productive than longer ones (Coyne & Coyne, 2011; McClure, 2014).

We found that compared to far-field industrial analogies, biological analogies significantly increase Novelty and tend to increase Elegance of concepts generated (H5 and H6). The former result reinforces Wilson et al.'s (2010) finding that exposure to a biological analogy prior to conceptual design tends to increase novelty of output vs. exposure to an industrial analogy. Novelty (i.e. originality) is an absolutely essential component of creativity (Hennessey & Amabile, 2010b; Mumford, 2000), and there is a positive relationship between the novelty of a product and consumers' willingness to pay for it (Dahl & Moreau, 2002). In addition, an elegant product may have an edge in the marketplace because its human interface elements delight customers (Han, Yun, Kim, & Kwahk, 2000; Oman, Tumer, Wood, & Seepersad, 2013). Correlation with overall creativity ratings was highest for Novelty (R = 0.877) and Elegance (R = 0.604). This result serves as a source of evidence that biomimicry (design by analogy to biology) is an
effective approach to product innovation that ought to be more broadly implemented by corporate R&D teams.

Novelty and Elegance, though given the bulk of the attention in assessments of creativity (Scott, Leritz, & Mumford, 2004), are not sufficient on their own. Relevance & Effectiveness is indispensable for solving a problem (Cropley & Cropley, 2010). Compared to biological analogies, we found far-field industrial analogies increase Relevance & Effectiveness of product concepts generated (H7). As such, we recommend a hybrid approach. A strategically designed brainstorming session should prime innovators with both far-field industrial and biological analogies to generate maximally creative ideas.

Many R&D managers encourage patent landscaping, a practice that produces far-field industrial analogies which can inform solutions to an innovation challenge. Far fewer recommend consultation with biologists/biological literature and/or outdoor excursions to identify biological analogies that can spark ideas. Given the results of this study, and the minimal upfront costs required, we strongly advise R&D managers pilot biomimicry. It is an approach that could significantly enhance their innovation toolkit, creating a competitive advantage over firms who neglect the biological realm as a ripe source of analogical ideation stimulus.

Acknowledgements

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CHAPTER VII

DYNAMIC IMPACT TESTING OF HEDGEHOG SPINES USING A DUAL-ARM CRASH PENDULUM

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Abstract

Hedgehog spines are a potential model for impact resistant structures and material. While previous studies have examined static mechanical properties of individual spines, actual collision tests on spines analogous to those observed in the wild have not previously been investigated. In this study, samples of roughly 130 keratin spines were mounted vertically in thin substrates to mimic the natural spine layout on hedgehogs. A weighted crash pendulum was employed to induce and measure the effects of repeated collisions against samples, with the aim to evaluate the influence of various parameters including humidity effect, impact energy, and substrate hardness. Results reveal that softer samples—due to humidity conditioning and/or substrate material used—exhibit greater durability over multiple impacts, while the more rigid samples exhibit greater energy absorption performance at the expense of durability.
This trend is exaggerated during high-energy collisions. Comparison of the results to baseline tests with industry standard impact absorbing foam, where in the spines exhibit similar energy absorption, verifies the dynamic impact absorption capabilities of hedgehog spines and their candidacy as a structural model for engineered impact technology.

Introduction

Hedgehog spines are naturally impact resistant. In the wild, hedgehogs climb trees and plants in search of food (Matthews, 1989; Vincent & Owers, 1986). They often fall (or jump to avoid predators) from heights exceeding ten meters. A falling hedgehog rolls into a ball and uses its dorsal muscles to erect its spines before impacting the ground at speeds up to 15 m/s (Matthews, 1974; Matthews, 1989; Vincent & Owers, 1986). Despite the velocity at impact, the animal survives unscathed due to the shock-absorbing capabilities of its spines, which buckle under load (Karam & Gibson, 1994; Vincent & Owers, 1986). Clearly, these spines serve a vital purpose beyond their ability to stab predators with their tapered ends (Matthews, 1989), especially considering how difficult it is to remove a hedgehog spine from a hedgehog (Carlier, 1893), versus a porcupine quill from a porcupine. The porcupine quill, which functions solely as a weapon, extracts from the pelt easily (Cho et al., 2012). Made of alpha-keratin, hedgehog spines have a unique internal morphology (Figure 7.1) (Gibson, Ashby, & Harley, 2010). When force is applied axially to an individual spine, it begins to “bow” laterally—closely following the Euler buckling model—once the critical buckling load is
achieved. If greater force is applied, the spine will continue to bow until roughly 200
times the critical buckling load is applied, at which point the spine ovalizes
(characterized by the Brazier effect) and fails, buckling locally. In testing the longitudinal
strength of spines with internal septa removed, Vincent & Owers (1986) discovered that
spines failed under far less axial load than with septa present. They concluded that it is
due to the internal morphology that failure is delayed to such a great magnitude beyond
the critical buckling load, as circumferential septa resist tensile load and reinforce the
spine’s cylindrical shape (Ashby, 2011; Brazier, 1927; Calladine, 1983; Gibson et al.,
2010a; Vincent & Owers, 1986). Measuring 1 mm diameter, 15–20 mm length (Vincent
& Owers, 1986) and weighing an average 3.5 mg, a hedgehog spine is a potential model
for innovation of high strength-to-weight ratio, impact resistant structures. It is likely
that engineered structures based on hedgehog spines would be more mechanically-
efficient in terms of specific strength (Gibson et al., 2010; Karam & Gibson, 1994),
material-efficient, and lighter weight than conventional structures (Beukers, Hinte, &
Vincent, 2005). Impact related studies in both engineered and natural armor materials
have attracted great attention in recent time (Bruet, Song, Boyce, & Ortiz, 2008; Chen et
al., 2011; Chintapalli, Mirkhalaf, Dastjerdi, & Barthelat, 2014; Huang, Durden, &
Chowdhury, 2011; Rudykh, Ortiz, & Boyce, 2015; Song, Ortiz, & Boyce, 2011).
Figure 7.1. (a) Photograph of a hedgehog spine, showing the bulbed end on the left, which attaches to the animal; (b) SEM of a spine's lateral cross-section; (c) CT scan of a spine's longitudinal cross-section.

Few experimental studies have been conducted on the mechanical properties of hedgehog spines. Vincent & Owers (1986) and Karam & Gibson (1994) conducted compression and bending tests on hedgehog spines, finding that the critical Euler buckling force for a single spine is roughly 6 N and that it takes 200 times the critical buckling load to initiate the Brazier effect (Vincent & Owers, 1986). Aside from additional verification by the aforementioned researchers, as well as some similar studies on the static mechanical properties of porcupine quills (Chou & Overfelt, 2011; Chou, Overfelt, & Miller, 2012; Torres, Troncoso, Diaz, & Arce, 2014; Yang, Chao, & McKittrick, 2013), there are no other documented mechanical tests on hedgehog spines.
and no literature on dynamic behavior of hedgehog spines during impact. However, understanding hedgehog spines' dynamic properties is of utmost importance for assessing their impact protection capabilities, which depend largely on an object's acceleration and mechanical energy absorption (Guskiewicz & Mihalik, 2011). Durability—consistent performance across multiple impacts—is also important for many applications such as concussion mitigation in football helmets (Pellman et al., 2004). However, hedgehog spine durability has not been investigated. Furthermore, Vincent & Owers (1986) and Karam & Gibson (1994) only tested static properties of individual spines instead of many spines grouped together similar to the arrangement on a hedgehog pelt (Figure 7.2), which typically have thousands of densely packed spines. Yet, there is reason to believe from observational evidence that spines' systematic grouping enhances their impact protection capabilities. Also, it is known that keratin's mechanical properties are affected by relative humidity of the material, wherein increased humidity generally softens keratin, while decreased humidity makes keratin harder and more brittle (Curiskis & Feughelman, 1983; McKittrick et al., 2012). In similar context, porcupine quills, which are also made of keratin and consist of a hard outer shell (cortex) and compliant porous core (medulla), exhibit considerably lower modulus and strength with increased humidity under axial loading (Chou & Overfelt, 2011; Chou et al., 2012; Torres et al., 2014). Humidity's effect on strength and energy absorption, durability, and failure point of hedgehog spines, however, has not been investigated. Adding to that, impact performance of hedgehog spines has not been compared to standard impact protection materials.
Figure 7.2. Densely packed spines embedded in the pelt of a dead hedgehog.

In this paper, a dual-arm "crash pendulum" is employed to measure the amount of energy absorbed by spine arrays embedded in a substrate across a variety of parameters, including substrate hardness, kinetic impact energy, relative humidity of the spines, and the effect of multiple hits. This work aims to fill the gaps in knowledge about hedgehog spines’ dynamic mechanics. The investigation involving a harder substrate examines how spines alone absorb impact energy by breaking since the epoxy provides fixed and rigid support boundary condition. The softer PU substrate, however, provides a simply support boundary condition, and works more as a system with the spines, contributing to impact absorption when allowing bending at the base of the spines, which more closely resembles spine-in-pelt behavior.

This work aims to provide scholarly contributions in the following areas:

1. First experimental demonstration to show that hedgehog spines function as an impact energy absorber.

2. First study of hedgehog spines as a group system, rather than individual spines, like in previous studies.
3. Identify key coupling elements and parameters to improve and influence the impact absorption performance of hedgehog spines system.

4. Emphasis on Biomimicry and reveal how engineered structural materials can benefit through a biomimicry approach.

Methodology

*Sample Preparation*

Intact spines were collected from a naturally deceased three-year old female African Pygmy hedgehog (*Atelerix albiventris/algirus*) donated to the study from Lawrence, KS. The pelt with all spines attached was skinned from the animal immediately following its death and stored in an oven set at 60° C for two weeks to facilitate plucking (Carlier, 1893; Matthews, 1989). Spines were individually plucked as needed for each sample, with each spine averaging about 15 mm in length. Spines sampled from all regions of the pelt exhibited similar length and diameter (l=15.70 ± 0.63 mm, d=0.98 ± 0.06 mm, N=53) so region of origin played no part in spine selection. Geographical uniformity of spines is corroborated by Vincent & Owers (1986). Spines could not be left in the pelt for impact testing due to the variable size, thickness and brittleness of the pelt as it decomposed, making it difficult to mount to the apparatus and adversely affecting data reliability. Using molded substrates, on the other hand, provided a consistent, flat, and sturdy base with unvarying mechanical properties. Test samples were generated by first mounting 130 spines vertically with the sharp end into a piece of packing foam. Next, the foam with spines was flipped and placed over a 5 cm
diameter circular substrate mold so that the bulbed ends of the spines were held
vertically embedded in the 3-5 mm thick substrate as it cured for 24 h (see schematic of
process in Figure 7.3(a) and Appendix C). The 5 cm diameter substrates had sufficient
surface area to yield statistically greater energy absorption than the no material
baseline. Mounting 130 spines in the 5 cm diameter substrates approximately mimicked
the average spine density on the natural model: 6.6 spines per square centimeter. Based
on Vincent & Owers (1986) as well as the authors’ own measurements, spine density
ranges from 3.9-11.6 spines per square centimeter, depending on how tightly the
animal is rolled into a ball. Two different substrate materials were used: MetLab #M135
(MetLab Corp, NY, USA), a hard epoxy rated Shore 82D provides a fixed and rigid
boundary condition to largely isolate the spines’ absorption capabilities from that of the
substrate, and Forsch URS5180 (Forsch Polymer Corp, CO, USA), a softer, more pliable
Shore 80A Polyurethane (PU) that provides a simply supported boundary condition by
allowing bending moment at the spine/substrate interface. The softer substrate more
closely mimics hedgehog flesh and may contribute to the impact absorption. For each
sample, the spines were mounted with the bulb end down into the substrate, again
mimicking the natural model. A typical finished sample is shown in Figure 7.3(b).
Figure 7.3. (a) Schematic of sample preparation; (b) a sample of hedgehog spines mounted vertically in a polyurethane (PU) substrate prior to testing.

To test humidity parameters, some samples were placed in a 100% relative humidity chamber for 48 h after the substrate was cured. These conditioned samples had estimated 85-90% relative humidity during the tests (samples were taken out of the chamber and mounted on the pendulum immediately before each test. A typical test with up to ten repeated impacts was conducted and finished within a 15 min period), while the unconditioned samples had 48-51% relative humidity according to local weather data.\(^7\) Despite a single hedgehog having thousands of spines, only six samples

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were generated. A large fraction of spines broke during extraction and we required intact spines for sample preparation. Also, we selected spines to eliminate variation in spine length and diameter (accepted range for l=15.5-16.0 mm, d=0.96-1.00 mm).

For a baseline comparison, a layer of foam from a Riddell Speed Classic football helmet was prepared for testing (hereafter referred to as ‘Foam’). It was cut down to match the footprint and thickness of the spine samples.

**Testing Apparatus**

Impact absorption testing on spines was conducted using a two-arm "crash pendulum" (Figure 7.4) similar to the setup in Ucar & Cengiz (2012). The system was designed to produce an axially impact loading without gravity effect during impact (Ucar & Cengiz, 2012). The crash pendulum can produce impact loading throughout the collision at adjustable velocity and therefore kinetic energy by adjusting the starting height, $h$ ($h = 0$ when the pendulum arm hangs straight down at rest). The two pendulum arms with weights bolted to the ends each swing with a radius of $l = 3.26$ m, connected to hinges by two aluminum extensions in a "V" shape. The total mass of each pendulum arm is $m = 43.32$ kg. Just above the two weights at roughly the center of mass was a rigid 1018 steel sample-mounting surface facing inward toward the other arm. The flat mounting pieces on the two arms were aligned to touch when the pendulum was at rest, hanging vertically under their hinges. Samples were mounted to one pendulum using double-sided tape. Additionally, a Canon PowerShot SD4500 IS high-speed video camera was mounted on a tripod facing the two pendulum arms, and
a backboard with calibrated markings was placed behind the arms to record data throughout each collision.

Figure 7.4. (a) Schematic of the pendulum apparatus arm motion during the course of one collision trial, with initial starting position (I), moment of collision (II), and post-collision back-swing (III); (b) photo of the apparatus at rest; (c) zoom-in detailing the colored stickers for video tracking and the location of the mounted sample (yellow arrow).
**Pendulum Impact Experimental Technique**

Mechanical symmetry between the right and left pendulum arms of the apparatus was established by experimentally testing collisions in both directions. All following trials on the pendulum were conducted by raising the left pendulum and dropping it toward the right pendulum (Figure 7.4(a)), which initially sat at rest with the sample attached to its collision plate (Figure 7.4(b)). All trials were conducted with a left arm starting height \( h \) at one of two points: 4° for 3 J collisions (low energy) and 6.5° for 8 J collisions (high energy) (Figure 7.4(a)-I), then analyzed using two independent techniques.

Using the high-speed camera and calibrated backboard, stopping points for the two pendulum arms were measured post-collision (hereafter referred to as ‘potential energy difference experimental technique’) (Figure 7.4(a)-III). Using the assumption that total kinetic energy of the pendulum arms immediately before and after the collision equals the starting and final potential energies, respectively of the arms, the total potential energy was calculated from the arms’ starting and stopping angles, where for any given pendulum angle:

\[
U = mgl(1 - \cos \theta)
\]

(1)

where \( U \) is the total potential energy in Joules of the given pendulum arm at its starting or stopping point; \( m \) is the total mass in kilograms of the pendulum arm; \( g \) is the acceleration due to gravity; \( l \) is the length in meters from the pendulum’s hinge to its center of mass; and \( \theta \) is the pendulum arm’s angle in degrees from vertical rest. The
small mass addition of the sample mounted to the right pendulum was considered negligible compared to the much larger total mass of the pendulum arm.

The total potential energy \( (U) \) of the arms at the stopping points was compared to the initial potential energy of the left arm at the starting point to determine the energy absorbed \( (\varepsilon) \) by the material during the collision:

\[
\varepsilon = U_{Li} - U_{Lf} - U_{Rf} \tag{2}
\]

and normalized absorbed energy \( (\varepsilon_{norm}) \),

\[
\varepsilon_{norm} = \frac{\varepsilon}{U_{Li}} \tag{3}
\]

where \( U_{Li} \) is the starting potential energy of the left pendulum, \( U_{Lf} \) is the final potential energy of the left pendulum after collision, and \( U_{Rf} \) is the final potential energy of the right pendulum after collision (Ucar & Cengiz, 2012). It is assumed that due to the low velocity of the pendulum arms, air resistance can be ignored (Mohazzabi, 2011) and all starting potential energy of the left arm was converted into kinetic energy immediately before collision. Likewise, it is assumed that all kinetic energy of the two arms immediately after collision was converted back into final potential energy of the two arms when they came to a stop. Other uncertainties that cannot be easily measured, such as the effect of arm vibration or friction in the hinges are accounted for by comparing experimental results to ‘Foam,’ as well as placing no samples between the two crash pendulum arms so that only the apparatus itself absorbs energy (hereafter referred to as 'No Material'), which will be discussed in Baseline Comparison under Results and Discussion.
Collisions were repeated on a given sample up to ten times or until the sample was destroyed beyond functionality, as determined through visual assessment (Table 7.1). In addition, collisions were repeated on the two baselines: ‘Foam’ and ‘No Material’, for a performance comparison that accounted for vibrational/frictional uncertainties in the apparatus, as well as to confirm the accuracy of the apparatus by calculating standard error across all hits, which was found to be under 3%.

Table 7.1. List of test samples, their relevant characteristics, and total collisions endured.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Substrate</th>
<th>Humidity</th>
<th>Total collisions (Impact energy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Epoxy</td>
<td>Dry</td>
<td>5 (Low)</td>
</tr>
<tr>
<td>B</td>
<td>Epoxy</td>
<td>Humid</td>
<td>5 (Low); 5 (High)</td>
</tr>
<tr>
<td>C</td>
<td>Epoxy</td>
<td>Dry</td>
<td>2 (High)</td>
</tr>
<tr>
<td>D</td>
<td>Epoxy</td>
<td>Humid</td>
<td>5 (High)</td>
</tr>
<tr>
<td>E</td>
<td>PU</td>
<td>Dry</td>
<td>5 (Low); 3 (High)</td>
</tr>
<tr>
<td>F</td>
<td>PU</td>
<td>Humid</td>
<td>5 (Low); 5 (High)</td>
</tr>
</tbody>
</table>

The pendulum arms’ starting and stopping angles in both directions from vertical ‘rest’ position were recorded manually at the time of experiment and then verified using the high-speed camera footage. These data points were then converted to potential energy $U$ using Eq. (1). Finally, the total energy absorbed ($E$) and normalized absorbed energy ($E_{\text{norm}}$) were plotted against the baselines over consecutive hits of the same sample in order to evaluate sample durability. The research team recorded visual post-mortem observations of sample damage with a Canon Powershot SD4500 IS.

The velocity and acceleration of the two pendulum arms throughout the collision were found by analyzing the high-speed camera footage with ProAnalyst software and applying fundamental equations of motion for calculation (hereafter referred to as ‘kinetic energy difference experimental technique’). High-speed video footage was
recorded by a Canon PowerShot SD4500 IS at the frame rate of 240 fps during each pendulum impact trial. Color stickers were applied to the pendulums around the sample-mounting locus for motion tracking. The stickers mirrored each other in terms of their locations on the left and right pendulums (Figure 7.4(c)). ProAnalyst Motion Analysis Software (Xcitex Inc., Cambridge, MA, USA) was used to track each pendulum’s stickers frame-by-frame in the high-speed video footage. Coordinate origin was set to the lower left corner of each video recording. Spatial distance in each video was calibrated using a known distance between backboard markings. Pendulum position coordinates (x, y) were exported after each video analysis. Distance travelled for each pendulum between frames (1/240 s) was calculated using $\sqrt{\Delta x^2 + \Delta y^2}$, and the speed was then calculated accordingly. Speed was plotted as a function of time for each pendulum (Appendix C, Figure A.2) and the resulting curves were smoothed. Acceleration-time curves were generated (Appendix C, Figure A.3) by taking first derivative of the speed-time curves (Appendix C, Figure A.2) in GraphPad Prism statistical software (GraphPad Software, Inc., La Jolla, CA, USA). The calculation of kinetic energy different experimental technique is explained in Appendix C, Figure A.4. A summary of energy absorption and acceleration values obtained from high-speed video analysis is presented in Appendix C, Table A.1.

Results and Discussion

In this section, the impact test results, as performed according to Table 7.1, are discussed in terms of the following parameters:
1. **Humidity** compares performance of the “dry” spines at 48-51% relative humidity (room environment) versus “humid” spines at 85-90% humidity.

2. **Impact energy** compares performance of spines at 3 Joules versus 8 Joules kinetic energy of the left pendulum immediately before impact.

3. **Substrate** compares performance of spines embedded in the Shore 82D epoxy versus those embedded in Shore 80A PU substrates.

4. **Baseline comparison** compares spine samples’ performance to ‘Foam’ and ‘No Material’.

**Humidity**

Two samples of 130 spines each embedded in Shore 82D epoxy are tested for this comparison. The hardness of the epoxy substrate almost entirely isolates the spines’ movement and function, since a fixed and rigid boundary condition is applied. Sample A has spines with approximately 48-51% relative humidity due to storage in normal room conditions, while sample B contains spines at 85-90% relative humidity after being stored in a 100% humidity chamber for 48 h prior to the experiment. Each is subjected to five consecutive collisions by the crash pendulum, with impact kinetic energy of 3 J.

The impact test results are analyzed independently by two different methods as described in Pendulum Impact Experimental Technique under Methodology (potential energy difference and kinetic energy difference). Each method has pros and cons: While calculating the kinetic energy difference is the most quantifiable way to analyze the results objectively, and many useful parameters can be extrapolated from the analysis.
(i.e. speed, acceleration, etc.), it does not account for the residual kinetic energy (velocity $v_L$) of the left pendulum after collision. On the other hand, estimating energy absorption using the potential energy difference experimental technique accounts for $V_L$ post-collision, but relies on a visual assessment of pendulum swing angle based on the backboard reference to determine $h$, and any angle $\theta$ less than 0.5° cannot be discerned by this method. The energy absorption results based on both methods, which provide a fuller picture than either method alone, are shown in Figure 7.5.

![Figure 7.5. Energy absorbed over repeated low energy (3 J) collisions. (a) Energy absorption calculated using the potential energy difference experimental technique. (b) Energy absorption calculated using the kinetic energy difference experimental technique (see Appendix C). ‘Foam’ and ‘No Material’ are plotted as mean ± s.d. Symbol (●) indicates low energy collisions. Blue is humid, red is dry.](image)

Results from both methods showed good agreement in trends of energy absorption over multiple impacts — the energy absorption performance of sample A (dry) constantly decreases over the course of multiple impacts, while that of sample B (humid) remains relatively consistent. It is noted that most spines in sample A broke and shattered during the second collision, whereas those in sample B resumed their original
form after collision. The brittleness of sample A is attributed to the properties of keratin, wherein the material hardens and stiffens when dried out, and softens and becomes more pliable when wet (Curiskis and Feughelman 1983).

In the third through fifth collisions, the energy absorption of sample A is less than during initial impact and continually degrades, likely due to the fact that most of the spines having already been destroyed by the second collision (Figure 7.6(a)). In contrast, sample B appears to maintain relatively consistent absorption capabilities throughout the five-collision trial (Figure 7.6(b)). The softer humid spines appear to be more resilient over repeated low-impact energy collisions, though they are unable to absorb as much kinetic energy during the initial collision compared to dry spines. In general, it can be concluded that stiffer spines may offer greater impact energy absorption capabilities, but at the cost of multi-hit durability. The overall estimated normalized absorbed energy ($\varepsilon_{\text{norm}}$), is higher when calculated from the kinetic energy difference (Figure 7.5(b)) because it does not account for post-collision residual velocity $v_f$. 
Figure 7.6. (a) Spines in Sample [A] show substantial breakage after five low energy collisions; (b) In contrast, the spines in Sample [B] remain mostly intact after five low energy collisions and five additional high energy collisions.

Impact Energy

Next, the influence of different impact speeds is evaluated by introducing two new samples of spines—sample C (dry) and D (humid), both prepared in epoxy substrates. In addition, since the spines in sample B (humid) remained intact after the low energy collisions (Figure 7.6(b)), they were further investigated to determine their durability by subjecting them to higher energy impacts for additional data points. Again, each sample was subjected to five repeated collisions, each with 8 J kinetic impact energy. Sample C was destroyed after two collisions so its use was discontinued. The energy absorption results are presented in Figure 7.7.
During the first collision, sample C absorbed a greater amount of energy than either humid spine sample (B and D). However, sample C was destroyed after only two hits, much more rapidly than both samples with humid spines (Figure 7.8(a)). This indicates that the greater impact absorption of the dry spines was due to permanent damage. The two humid spine samples (B and D), on the other hand, did not shatter and resumed their original form after each collision (Figure 7.6(b), 7.8(b)), demonstrating the resiliency of the softer, humid spines. This is especially so for sample B, which endured a total of ten collisions. It is worth noting, however, that unlike in the low energy test (Figure 7.5), the humid spines in the high-energy test underwent gradual energy absorption depletion over consecutive hits (Figure 7.7). Additionally, while all samples absorbed more total energy than during the low energy test, they absorbed a smaller percentage of the initial impact energy (normalized absorbed energy ($\epsilon_{norm}$))
during the high energy test versus the low energy test. This suggests that the capability of hedgehog spines to absorb energy becomes saturated during high-energy collisions, resulting in greater damage over multiple hits at higher impact speeds.

Figure 7.8. (a) Spines of dry Sample [C] show significant breakage after just two 8 J collisions; (b) most spines of humid Sample [D] remain intact with just minor damage after five consecutive 8 J collisions.

**Substrate**

In order to more accurately model the hedgehog impact absorption capabilities, spine samples E (dry) and F (humid) were embedded in a softer, more pliable Shore 80A PU substrate. Like the pelt on a hedgehog, the softer substrate may contribute to the impact absorption capabilities of the spine system by increasing the spines’ freedom to rotate at the junctions of the substrate and spine bases and allowing load transfer into the substrate via the embedded bulbed ends of the hedgehog spines (Vincent & Owers, 1986). The two samples were first subjected to five consecutive collisions in low energy tests, and subsequently to five consecutive collisions in high energy tests, since they were still intact (sample F showed no signs of damage while sample E had very minimal damage).

At first glance, the energy absorption results analyzed by two independent methods do not seem to agree with each other in low energy impact tests. The
calculated result using the kinetic energy difference experimental technique (Figure 7.9(b)) shows that the energy absorption performance for both sample E and F is relatively consistent throughout five collisions during the test. In contrast, the result calculated using the potential energy difference experimental technique (Figure 7.9(a)) shows a drastic dip at the third and fourth collision before starting to recover. Recall that the difference between these two methods is the inclusion of the left pendulum’s residual energy when calculations are performed using the kinetic energy difference experimental technique. By combining results from both methods, the data suggests that the energy transferred from the left pendulum to the right across five different collisions remained consistent during the low energy test (Figure 7.9(b)). The left pendulum’s residual energy after each collision steadily increases and peaks at the third and fourth impact before returning to the initial state (Figure 7.9(a)). The increase of the left pendulum’s residual energy can be explained by the softer substrate. In the samples with a softer substrate, spines have more freedom to rotate at the junctions of the substrate and spine bases. Therefore, the early collisions cause the spines to “flatten,” or get pushed and reoriented closer to parallel to the substrate. It is suspected that the movement of the spines limits the amount of energy that can be transferred to the right pendulum during the short collisions, and allows more energy to be kept on the left pendulum at the same time. This agrees with our observation from the samples after the test: while few spines — especially those in the humid samples — broke or shattered, it was noted that many spines were flattened (Figure 7.10), something that did not occur with samples in epoxy substrates. A similar trend was observed in the high
energy test (Figure 7.9(c)), though the change in absorption across collisions is less dramatic. This indicates that the early high energy collisions “flattened” the spines further even when the sample had already endured five collisions in the low energy test. The dip likely signifies the point where the spines have the highest freedom to move before reaching maximum “flatness”.

Figure 7.9. Energy absorbed by samples embedded in polyurethane (PU) substrates over repeated collisions. (a, c) Energy absorption calculated using the potential energy difference experimental technique. (b, d) Energy absorption calculated using the kinetic energy difference experimental technique (see Appendix C). ‘Foam’ and ‘No Material’ are plotted as mean ± s.d. Symbol (●) indicates low energy collisions; (▲) indicates high energy collisions. Blue is humid, red is dry.
Figure 7.10. (a) Side and (b) top view of Sample [E]. Although some spines broke, many were pressed flat against the PU substrate.

Evidently, despite the researchers’ effort to closely mimic the spine-pelt system of the hedgehog, the PU substrate samples still lacked a control mechanism to keep spines erect from the surface during repeated hits, analogous to the animal’s dorsal muscles. Indeed, the rigid epoxy substrate can adequately keep spines erect after impact, as it allows virtually no spine movement. The results suggest that the first hit reoriented the spines embedded in PU because of the greater “wiggle room” in the elastic substrate, and for each hit following, the spines were pushed closer to parallel to the substrate. On a hedgehog, this could also happen, except the animal has muscles attached to the base of the spines which it contracts to erect the spines hit after hit (Reeve, 1994). As an elastomer, the PU substrate comes closer than epoxy to mimicking the hedgehog pelt system by allowing load transfer into the substrate via the embedded bulbed ends of the hedgehog spines, similar to how impact loads are likely transferred into the hedgehog skin.
Baseline Comparison

In each of the above experiments, energy absorption results of the samples are plotted against those of a sample of foam from a Riddell Speed Classic football helmet cut to match the footprint and thickness of the spine samples (‘Foam’), and a second baseline where nothing was placed between the two crash pendulum arms and only the apparatus itself absorbed energy (‘No Material’). The purpose is two-fold: the ‘Foam’ baseline helps measure how hedgehog spines perform as an impact material versus industry standard impact absorbing foam, and ‘No Material’ demonstrates the amount of energy absorbed by the apparatus alone due to friction, vibration, or any other unaccounted-for uncertainty, thus giving to the data perspective as the apparatus’ “zero point.” Despite inherent experimental uncertainties, the results from repeated collisions with ‘Foam’ and with ‘No Material’ show consistency throughout the experiment, confirming the repeatability of the pendulum technique. A t-test analysis of the energy absorption between ‘Foam’ and ‘No Material’ shows that the crash pendulum apparatus has the resolution to tell them apart and further supports the results (Figure 7.11). Spine samples generally performed similarly to ‘Foam’; indeed some absorbed slightly less while others absorbed slightly more. This confirms hedgehog spines’ inherent dynamic impact absorption capabilities.
Figure 7.11. Column plot (mean ± s.d.) showing significantly different impact absorption ability of ‘Foam’ and ‘No Material’ across all collisions. (a) Energy absorption in low energy tests; (b) energy absorption in high energy tests. In both low and high energy tests, ‘Foam’ always shows significantly higher energy absorption ability over ‘No Material.’ ** indicates P<0.01, **** indicates P<0.001.

Protection vs. Durability

In the human brain, it is known that certain acceleration of the head is likely to cause injury such as concussion (Ommaya & Gennarelli, 1974). Therefore, an impact material that minimizes the acceleration experienced during a collision by absorbing as much kinetic energy as possible can reduce the likelihood of concussion, or other similar injury and damage. Figure 7.12 compares the acceleration of the pendulum during impact for each sample across all collisions. Overall, during low energy collisions (Figure 7.12(a)), all samples except the dry epoxy sample experienced significantly lower acceleration when compared to ‘No Material.’ It seems that at slower collision speeds, the individual parameters tested above on the spine samples make little difference to acceleration. Interestingly, for the high-energy collisions (Figure 7.12(b)), the exact opposite pattern occurred — only the dry epoxy sample experienced significantly lower acceleration when compared to ‘No Material.’ One explanation for the seemingly
impressive performance of the dry epoxy is that the sample only lasted for two collisions before complete destruction, during which it absorbed more energy than any other sample. The most significant takeaway is that on average, the spines absorb about the same energy as ‘Foam,’ and therefore reduce acceleration throughout the collision by about as much as ‘Foam.’

Figure 7.12. Column plot (mean ± s.d.) showing maximum acceleration experienced by the impacted (right) pendulum across all collisions. (a) Compared to ‘No Material’, all samples except Epoxy Dry (Sample A) experienced significantly lower acceleration in low energy tests. (b) Compared to ‘No Material’, only Sample A (Epoxy Dry) experienced significantly lower acceleration in high energy tests. * indicates P<0.05, **indicates P<0.01.

The other important metric of this study is multi-hit durability. That is, the number of hits that a given sample can endure while maintaining consistent impact absorption performance. In general, there is an observed trade-off. A sample either absorbs a large amount of impact energy during the collision, even outperforming ‘Foam’ on occasion as with sample C in Figure 7.7, but at the cost of poor durability – wherein performance deteriorates rapidly after the first couple of hits. On the other end of the spectrum, the softer spine samples exhibit far greater durability, with nearly
consistent absorption throughout all collisions, yet energy absorption is roughly equal, if not lower than ‘Foam.’ An ideal impact protection material balances these two parameters to match the needs of a given application. Perhaps further optimization of the impact technology could concurrently increase performance of both metrics so that one need not be sacrificed to realize the other.

Conclusions

This study is the first to investigate the impact energy absorption capability of hedgehog spines beyond anecdotal biological evidence, measuring absorption trends over multiple impacts in a lab setting. Past studies have just suggested the possibility of applying the structural model to impact protection applications rather than demonstrating them. Additionally, no other study has investigated the effect of the densely packed spine arrangement analogous to the hedgehog model, nor have any parametric studies examined the effect of humidity conditioning on hedgehog spines. Our Results show that humidity softens keratin, making spines more durable but less energy absorbent. Greater impact speed decreases durability, but not initial energy absorption. It is also revealed that softer, elastic substrate adds energy absorption but samples deform more rapidly.

When samples are arranged in an orientation analogous to the natural model, hedgehog spines demonstrate impact absorption capabilities that confirm their role in the protection of hedgehogs during falls. This study demonstrates that in certain conditions, hedgehog spines can absorb as much, if not more, than industry standard
impact-absorbing foam. However, there is a definite balance between impact absorption and multi-hit durability, as samples that absorb greater amount of impact energy remain intact for fewer hits due to greater damage, while other samples that absorb less impact energy have greater resilience and can endure significantly more collisions. However, these results only confirm the capabilities of the spine system as a whole. Further studies are still needed to understand the specific roles in impact absorption and durability played by the spines’ internal structure, the layout of multiple adjacent spines, the material of the spines, the specific contribution by the substrate material, and a methodology to better control the ‘flattening’ of spines against the substrate, as each of these variables could alter results.

This investigation is one of the first of likely many steps towards designing and optimizing higher performing engineered impact and structural materials. By demonstrating how hedgehog spines exhibit similar impact energy absorption as a sample of foam from a Riddell Speed Classic football helmet, the authors provide evidence that hedgehog spines are a viable biomimetic model for a commercial impact resistant material. After all, the spines used in this study were harvested from a dead animal, and despite the researchers’ best efforts to maintain them, they may have deteriorated prior to testing. Specially designed and synthetically engineered spine structures—built using 3D additive manufacturing or other means—could be optimized for even better impact protection, as demonstrated with the microstructure found in Chiton teeth (de Obaldia, Jeong, Grunenfelder, Kisailus, & Zavattieri, 2015). Biomimicry has proven time and again to be a reliable and fruitful innovation technique for inspiring
new products such as VELCRO, which was developed based on how burrs stick to animal fur (Dickinson, 1999). Perhaps a hedgehog-inspired impact protection technology is a forthcoming feat of biomimicry.

Acknowledgements

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CHAPTER VIII

STATIC FLEXURAL PROPERTIES OF HEDGEHOG SPINES CONDITIONED IN COUPLED TEMPERATURE AND RELATIVE HUMIDITY ENVIRONMENTS

In Progress:


Abstract

Hedgehogs are agile climbers, frequently scaling trees and plants to heights exceeding 10 meters while foraging insects. Hedgehog spines (a.k.a. quills) provide fall protection by absorbing shock and could offer insights for the design of lightweight, material-efficient, impact-resistant structures. There has been some study of flexural properties of hedgehog spines, but an understanding of how this keratinous biological material is affected by various temperature and relative humidity treatments, or how spine color (multicolored vs. white) affects mechanics, is lacking. To bridge this gap in the literature, we use three-point bending test to analyze the effect of temperature, humidity, spine color, and their interactions on flexural strength and modulus of hedgehog spines. We also compare specific strength and stiffness of hedgehog spines to
conventional engineered materials. We find hedgehog spine flexural properties can be
dinely tuned by modifying environmental conditioning parameters. White spines tend to
be stronger and stiffer than multicolored spines. Finally, for a vast majority of
temperature and humidity conditioning parameters, hedgehog spines are ounce for
ounce stronger than 201 stainless steel but as pliable as styrene. This unique
combination of strength and elasticity makes hedgehog spines exemplary shock
absorbers, and an incredibly suitable reference model for biomimicry.

Introduction

Hedgehogs are agile climbers (Matthews, 1989). In the wild, these small
mammals scale trees and plants to heights exceeding 10 meters while foraging insects
(Matthews, 1989; Vincent & Owers, 1986). When a hedgehog needs to descend from an
above ground perch quickly—to escape a predatory owl, for example—it will roll into a
ball and simply drop to the ground (Matthews, 1989; Vincent & Owers, 1986). The
hedgehog survives impact because its spines (a.k.a. quills) absorb shock. The shock
absorbing function of hedgehog spines distinguishes them from porcupine quills, which
can support considerable loads (Yang et al., 2013; Wen Yang & McKittrick, 2013), but
have a primary function of self-defense via predator tissue penetration (Cho et al.,
2012). Tissue penetration is the primary function of many slender structures in nature,
such as honeybee and paper wasp stingers (Zhao et al., 2015), and mosquito
proboscises (Aoyagi, Izumi, & Fukuda, 2008). The impressive shock absorbing properties
of slender hedgehog spines is unique.
In the field of mechanical engineering, biomimicry has led to a number of technological advances including human bone-inspired building frames with reduced seismic vulnerability (Mendez, 2010), woodpecker-inspired electronics housing (Yoon & Park, 2011), nacre-inspired deformable glass (Valashani & Barthelat, 2015), and mantis shrimp-inspired high-performance carbon fiber–epoxy composites (Grunenfelder et al., 2014). Hedgehog spines, a less studied biological tissue, could offer additional insights for the design of lightweight, material-efficient, impact-resistant structures (Gibson et al., 2010; Ma, Chen, Zhao, & Zhao, 2008).

Only a few mechanical studies of hedgehog spines have been conducted (Vincent & Owers, 1986; Karam & Gibson, 1994; Swift, Hsiung, Kennedy, & Tan, 2016). Under loading, hedgehog spines buckle elastically, resisting permanent deformation unless exposed to 200 times the critical buckling load (Vincent & Owers, 1986; Wang, Yang, McKittrick, & Meyers, 2015). Given this elastic buckling (i.e. bowing) behavior, a thorough investigation of static flexural properties is necessary to provide a fundamental understanding of the way hedgehog spines absorb impact energy. Some work has been done in this area. In 1986, Vincent and Owers conducted four-point bending on whole hedgehog spines and observed a load-to-failure of 0.392 ± 0.0276 GPa (Vincent & Owers, 1986). In order to perform four-point bending on hedgehog spines, Vincent & Owers had to reinforce the load-bearing surfaces of the spines with plastic tubing to prevent premature failure at anvil contact points (Vincent & Owers, 1986). This manipulation may have impacted their data. Three-point bending is the
technique of choice for this study because it allows for flexural testing of unmodified hedgehog spines.

Hedgehog spines are made of alpha-keratin. Researchers have found keratin’s flexural strength and modulus are inversely related to temperature and relative humidity (B. Wang et al., 2015). For example, increasing temperature weakens rat stratum corneum (Papir, Hsu, & Wildnauer, 1975) and marine snail (whelk) egg capsules (Miserez, Wasko, Carpenter, & Waite, 2009), two other keratinous biological materials. Likewise, increases in relative humidity result in decreased tensile strength as well as axial and circumferential moduli of keratinous North American porcupine quills (Chou & Overfelt, 2011). Thus, effect of temperature and humidity conditioning parameters on hedgehog spines is of interest. Swift et al. (Swift et al., 2016) investigated the effect of humidity conditioning on hedgehog spines using a weighted crash pendulum to impact 130-spine arrays mounted in thin substrates. Compared to dry samples, wet samples exhibit increased durability (i.e. ability to withstand multiple impacts without visible damage) but reduced energy absorption. We advance understanding of the effect of conditioning parameters on hedgehog spines by further differentiating and better controlling humidity conditions, adding temperature as a potentially interacting variable, and focusing on mechanics of individual hedgehog spines rather than spine arrays.

Coloration is another variable of interest. Hedgehog pelts are covered in a mix of multicolored and white spines (2.44 ± 0.44:1, N = 2,112) (Figure 8.1). The midsections of the predominant multicolored hedgehog spines appear darker, perhaps due to higher
concentration of melanin pigment, which absorbs light over a wide range of wavelengths (Menon & Haberman, 1977). Though there is currently no experimental evidence that melanin pigment is present in the midsections of multicolored hedgehog spines, we infer that there could be, due to the darker color. A higher concentration of melanin correlates with increased mechanical strength of other biological tissues, such as plant cell walls, insect cuticle (Riley, 1997), bloodworm jaws (Moses, Harreld, Stucky, & Waite, 2006; Moses, Mattoni, Slack, Waite, & Zok, 2006), and feather barbs (Butler, 2004). Therefore, we test to see if multicolored spines are stronger than white spines. To our knowledge, no published study has examined the effects of spine color on hedgehog spine mechanics. Finally, we compare the flexural properties of hedgehog spines with conventional engineered materials to determine the suitability of hedgehog spines as a model for biomimicry.

Figure 8.1. Multicolored vs. white hedgehog spines. A multicolored hedgehog spine (A) and a white hedgehog spine (B).

This work provides scholarly contributions in the following areas of investigation:

1. Analyzing the effect of various temperature treatments on static flexural properties of hedgehog spines.
2. Examining the effect of various relative humidity treatments on static flexural properties of hedgehog spines.

3. Expounding the effect of spine color on static flexural properties of hedgehog spines

4. Elucidating interaction effects of various temperature and relative humidity treatments, as well as spine color, on static flexural properties of hedgehog spines.

5. Evaluating and comparing specific strength and stiffness of hedgehog spines vs. conventional engineered materials.

Materials and Methods

Sample Preparation

An uncured hedgehog pelt, donated by West Coast Hedgehogs (Corvallis, OR) was removed with all spines attached from a female African Pygmy (*Atelerix albiventris*), aged 1.5 years, which died earlier that day of natural causes. The hedgehog had shed its juvenile spines and grown a mature coat of adult spines. Upon receipt, the pelt was stored in a freezer at -20°C for three months to prevent deterioration. Spines were clipped from the thawed pelt at the spine-pelt connection point. Seventy-two mature spines of approximately equal dimensions (~16 mm in length and ~1 mm in diameter), were selected for testing. These spines included 36 multicolored and 36 white. Pelt location played no part in spine selection since spines sampled from all regions of the pelt exhibited highly similar length and diameter (Swift et al., 2016).
Prior to conditioning, individual specimens were weighed with a CAHN 21 Automatic Electrobalance (CAHN Instrument Company, Paramount, CA) (3.76 ± 0.38 mg, N=72). Spines were conditioned in each coupled temperature and relative humidity environment (Table 8.1) before mechanical testing. Temperature and relative humidity values were chosen based on past studies of keratinous biological materials (Chou & Overfelt, 2011; Miserez et al., 2009; Papir et al., 1975). We do not attempt to recreate hedgehog habitat conditions. Highest and lowest conditioning parameters are quite extreme to make it easier to detect statistically significant differences in spine mechanics across conditions. Using extreme parameters, we can interpolate intermediary mechanical behavior, including within biologically-relevant ranges. For each unique temperature and relative humidity combination, six specimens (three multicolored and three white) were placed in an open Styrofoam cube and conditioned for 48 hours (per ASTM D790-15e2) in a Z8-Plus (Cincinnati Sub-Zero, Cincinnati, OH) temperature and humidity chamber. Upon removal from the chamber and prior to lidding, a two-way humidity pack was added to the Styrofoam cube containing the spines in an attempt to maintain humidity at conditioned level.

Table 8.1. Conditioning parameters and their abbreviations

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Relative Humidity (RH)</th>
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</thead>
<tbody>
<tr>
<td>1°C – Low</td>
<td>LT35 LT60 LT70 LT85</td>
</tr>
<tr>
<td>23°C – Room</td>
<td>RT35 RT60 RT70 RT85</td>
</tr>
<tr>
<td>80°C – High</td>
<td>HT35 HT60 HT70 HT85</td>
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*Three-Point Bending*

Three-point bend tests were conducted on the 72 conditioned specimens using an Instron 5582 (Instron, Norwood, MA), a 500 N loading anvil with a 2 mm cross-
sectional diameter loading tip, a 12 mm support span, and a displacement rate of 0.5 mm/min (Figure 8.2). Each specimen was deflected until rupture occurred and there was a sudden load drop in the load-displacement curve, or to a maximum 3 mm displacement, whichever came first. Throughout testing, lab facility temperature ranged 22-28°C and relative humidity ranged 50-60%. Post bending, the diameter of each specimen directly adjacent to its bend vertex, the point of peak stress concentration during bending, was measured (0.93 ± 0.04 mm, N=72). Load-displacement data was normalized by spine diameter. Flexural strength equaled max load (N), and flexural modulus equaled bending stiffness (N/mm) (the initial slope of the load-displacement curve).

For comparative purposes, three-point bend tests were also conducted on conventional engineered materials, namely three stainless steel #201 rods (1 mm diameter), three stainless steel #316 tubes (1.06 mm outer diameter; 0.69 mm inner diameter), three carbon fiber rods (1 mm diameter), three nylon 6/6 rods (1.69 mm diameter), and three styrene rods (1.19 mm diameter) cut to 16 mm length, weighed, and conditioned at RT35. To compare specific strength and stiffness of hedgehog spines versus conventional materials, load-displacement data was normalized by specimen weight, rather than diameter.
Computed Tomography

Micro Computed Tomography (Micro-CT) is useful for inspecting fine scale internal structure. Hedgehog spines have unique internal morphology with features as small as 15 μm thick (Gibson et al., 2010), making them an appropriate candidate for Micro-CT. A SKYSCAN 1172 Micro-CT Scanner (Bruker MicroCT, Kontich, Belgium) was used to elucidate structure and damage mechanisms via cross-sectional imaging of specimens post-bending. The scanner was set at a source voltage of 60 kV, a current of 167 μA, and pixel size of 2.9 μm.
A Phoenix Nanotom-MTM 180 Nano-CT Scanner (GE Sensing & Inspection Technologies GmbH, Germany) was used to elucidate structure and damage mechanisms via 3D reconstruction of specimens post-bending. The scanner was set at a source voltage of 80 keV, a current of 40-80 μA, and voxel size of 0.8-1.7 μm for highest resolution scans. High single image averaging was used (n=6-12) and 800-1500 scans per acquisition was typical. After reconstruction of the 3D virtual object utilizing Phoenix software, analysis of the reconstructed volumes was investigated using VGStudio MAX 2.1 software.

*Hygroscopic Moisture Measurement*

For each temperature condition and color group, the weight of 10 spines was tracked across six different RH conditions (0%, 32%, 62%, 72%, 84%, 100%). Relative humidity conditions were maintained using controlling agents placed in a sealed chamber (0%: desiccant and nitrogen purge; 32-84%: two-way humidity packs; 100%: water dish). Individual spines were conditioned for 48 hours at each relative humidity level before being weighed with a CAHN 21 Automatic Electrobalance (CAHN Instrument Company, Paramount, CA).

*Statistical Methods*

T-tests were performed to determine whether differences in flexural strength and flexural modulus of multicolored and white spines conditioned at 12 unique temperature and relative humidity combinations (Table 8.1) were statistically
significant. Two three-way analyses of variance (ANOVAs) were performed to estimate the main effects of temperature, humidity, and spine color, along with their interactions, on flexural strength and flexural modulus. Independent variables were coded as categorical. Temperature had three levels (1°C, 23°C, and 80°C), humidity had four levels (35%, 60%, 70%, and 85%), and spine color had two levels (multicolored and white). We verified homogeneity of variances and normality of the residuals to meet assumptions of ANOVA. ANOVAs were performed with JMP® Pro 12 (SAS Institute, Cary, NC).

Results and Discussion

Relative Humidity

Flexural strength and modulus of multicolored spines conditioned at room temperature (23°C) decreases as relative humidity increases (Figure 8.3). This observed mechanical response of individual multicolored hedgehog spines to increasing humidity corresponds with what has been observed of hedgehog spine arrays (Swift et al., 2016) and other keratinous biological materials, like North American porcupine quills (Chou & Overfelt, 2011). Alpha-keratin comprises a microfibril-reinforced amorphous matrix (Feughelman, 1959). The microfibrils are insoluble in water, but the amorphous matrix absorbs ambient water (McKittrick et al., 2012). Absorbed water likely acts as a plasticizer at room temperature, weakening the material (Vincent, 1990).
Figure 8.3. Relative humidity effect at room temperature. Average load-displacement curves (A), flexural strength (B), and flexural modulus (C) of multicolored hedgehog spines conditioned at room temperature (23°C) / variable humidity. Load-deflection data normalized by spine diameter. * P≤0.05; ** P≤0.01; *** P≤0.001 **** P≤0.0001.

Flexural strength and relative humidity of multicolored spines conditioned at high temperature (80°C) is also inversely correlated; but flexural modulus and relative humidity are not correlated (Figure 8.4). Spines conditioned at HT35 are brittle, and break into two jagged-edged segments between 1.5 and 2 mm displacement (Figure 8.5A 5-6, 5B 2), whereas spines conditioned at HT60, HT70, and HT85 are ductile, and exhibit typical buckling behavior without breakage (Figure 8.5A 2-4, 5B 1). Breaks are clean and do not cause deformation to internal structure (Figure 8.5A 5-6, 5 B2). Typical buckling behavior is characterized by pre-buckling ovalization (Figure 8.5A 3) followed
by inward folding of the spine wall on the compression side (Figure 8.5A 2,4, 5B 1).

Internal structure on the extension side of buckled spines remains mostly unaffected (Figure 8.5A 2,4, 5B 1). Hedgehog spines exposed to high temperatures for prolonged periods may thus exhibit a semi-reversible brittle to ductile transition between 35 and 60% relative humidity.

Neither flexural strength nor flexural modulus of multicolored hedgehog spines conditioned at low temperature (1°C) is correlated with relative humidity (Figure 8.6). For spines conditioned at low temperature (1°C), the only statistically significant difference is between flexural strength of LT35 and LT70 (LT35 > LT70; P≤0.05).

Figure 8.4. Relative humidity effect at high temperature. Average load-displacement curves (A), flexural strength (B), and flexural modulus (C) of multicolored hedgehog spines conditioned at high temperature (80°C) / variable humidity. Load-deflection data normalized by spine diameter. **** P≤0.0001.
Figure 8.5. CT scans elucidating structure and damage mechanisms. Panel A: Cross-sectional images of pre-test structure, observed across all specimens regardless of color (1), typical buckling behavior (2, 3, 4), and atypical breakage (5, 6) observed only at high temperature, low humidity. Panel B: 3D reconstruction of typical buckling behavior (1) and atypical breakage (2), observed only at high temperature, low humidity.
**High Temperature**

We observed a general trend that spines conditioned at high temperature exhibit greater flexural strength than spines conditioned at room temperature across all relative humidity treatments (Figure 8.7). However, differences are only statistically significant at extreme relative humidity treatments. Flexural strength of HT35 is significantly greater than RT35 (P≤0.001) and the flexural strength of HT85 is significantly greater than RT85 (P≤0.001). One possible explanation for this observed trend is that high temperatures may alter alpha keratin structure. Recall, alpha-keratin comprises a microfibril-reinforced amorphous matrix (Feughelman, 1959). High
temperature may initiate a greater degree of intermolecular crosslinking, resulting in samples with more microfibrils, and thus heightened material strength and stiffness. High temperature-induced microfibril formation would also reduce water absorbability because alpha keratin microfibrils are insoluble in water, whereas the amorphous matrix absorbs ambient water (McKittrick et al., 2012). An increased proportion microfibrils versus amorphous matrix, resulting in reduced water absorbability, could explain why samples conditioned at high temperature show decreased susceptibility to the weakening effects of humidity versus samples conditioned at room temperature (Figure 8.3B versus Figure 8.4B).
To test this hypothesis, we compared hygroscopic properties of multicolored spines conditioned at high temperature / variable humidity to multicolored spines conditioned at room temperature / variable humidity using the method described in Hygroscopic Moisture Measurement under Methods. Results, plotted in Figure 8.8 (HT Multi vs. RT Multi), show spines conditioned at high temperature (HT Multi) absorb significantly less water (P≤0.001) than spines conditioned at room temperature (RT Multi) across relative humidity treatments ranging 32-84%. This supports the hypothesis that high temperatures initiate microfibril formation, increasing material strength and stiffness while decreasing water absorbability.

![Figure 8.8. Hygroscopic properties of hedgehog spines. Weight fraction water uptake in multicolored spines at high temperature (80˚C) and room temperature (23˚C) / variable humidity, and white spines at room temperature (23˚C) / variable humidity. The weight of a spine at 0% RH is defined as weight_{dry} with any increase in weight above weight_{dry} assumed to reflect water uptake. Therefore, water content (%, w/w) is calculated (weight_{measured} - weight_{dry}) / weight_{dry}.](image)

**Low Temperature**

Multicolored hedgehog spines conditioned at low temperature (1˚C) appear to be less susceptible to humidity effects than spines conditioned at high temperature (80˚C) or room temperature (23˚C). In fact, spines conditioned at low temperature...
maintain relatively consistent performance in terms of flexural strength (and flexural modulus) across all relative humidity treatments (Figure 8.9) at a max load level roughly equal to spines conditioned at RT35. These results make intuitive sense. The saturation pressure of water vapor in moist air varies with temperature. Smaller quantities of water vapor saturate cold air. Larger quantities are required to saturate the same volume of hot air. If the maximum absolute humidity of 1˚C (cold) air in the temperature and humidity chamber is small, increasing relative humidity from 35% to 85% would have imperceptible effect on environmental wetness (effect below detection limit). Conditioning parameters LT35, LT60, LT70, and LT85 may have produced an environment very similar to RT35 in terms of absolute humidity.

Figure 8.9. Low temperature effect. Flexural strength (A) and flexural modulus (B) of multicolored hedgehog spines conditioned at low temperature (1˚C) versus multicolored hedgehog spines conditioned at room temperature (23˚C) across varying relative humidity treatments. Load-deflection data normalized by spine diameter. **** P≤0.0001.
Spine Color

Based on statistical t-tests, the mechanical performance of multicolored hedgehog spines does not significantly differ from white hedgehog spines in any coupled temperature and humidity environment. However, for spines conditioned at room temperature (23°C), multicolored spines tend to be more susceptible to humidity effects (decreased flexural strength and modulus with increasing relative humidity treatments) compared to white spines (Figure 8.10). Like multicolored spines, flexural strength and modulus of white spines conditioned at room temperature decreases as conditioning chamber RH increases, but for white spines, this trend is less pronounced. The observed difference in mechanical behavior depending on spine color motivated an experiment comparing hygroscopic properties of multicolored versus white spines at room temperature / variable humidity using the method described in Hygroscopic Moisture Measurement under Methods. Results are plotted in Figure 8.8 (RT Multi vs. RT White) and show there is no significant difference in water uptake behavior of multicolored and white spines at any relative humidity treatment. Water uptake behavior thus does not explain differences in multicolored and white spine mechanics.
Figure 8.10. Relative humidity effect on multicolored vs. white spines at room temperature. Average load-displacement curves (A), flexural strength (B), and flexural modulus (C) of multicolored hedgehog spines conditioned at room temperature (23°C) / variable humidity versus white hedgehog spines conditioned at room temperature / variable humidity. Load-deflection data normalized by spine diameter.

Interaction Effects

ANOVAs were performed to estimate the main effects of temperature, humidity and spine color, along with their interactions, on flexural strength and flexural modulus.

An ANOVA shows significant effects of humidity (P<0.0001), temperature (P<0.0001), spine color (P=0.0007) and the interactions between humidity x temperature (P<0.0001), humidity x spine color (P=0.0258), and humidity x temperature x spine color (P=0.0024) on flexural strength (Table 8.2). The ANOVA corroborates an
inverse relationship between flexural strength and relative humidity, with samples conditioned at room temperature and high temperature showing heightened susceptibility to the weakening effects of humidity, regardless of color. Flexural strength dipped at room temperature (LS-mean = 2.879 ± 0.0549 N max load, versus 3.2541 ± 0.0549 N max load at low temperature and 3.8211 ± 0.0549 N max load at high temperature). White spines tended to be stronger (LS-mean = 3.4334 ± 0.0448 N max load) than multicolored spines (LS-mean = 3.2031 ± 0.0448 N max load). This result undercuts our hypothesis that multicolored hedgehog spines contain higher concentrations of melanin pigment, which may increase their strength when compared to white spines (Butler, 2004; Menon & Haberman, 1977; Moses, Harreld, et al., 2006; Moses, Mattoni, et al., 2006; Riley, 1997). In addition, Raman spectroscopy on multicolored spines is inconclusive; we did not detect melanin using this technique. Future studies characterizing the material properties of dark versus light sections of hedgehog spines, using techniques like nanoindentation and dynamic mechanical spectroscopy, may help explain mechanical differences between multicolored and white spines.

Table 8.2. Analysis of variance of the effect of humidity, temperature, spine color, and their interactions on flexural strength. * P≤0.05; ** P≤0.01; *** P≤0.001 **** P≤0.0001.

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>SS</th>
<th>F Ratio</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Humidity</td>
<td>3</td>
<td>16.5760</td>
<td>76.3310</td>
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<tr>
<td>Temperature</td>
<td>2</td>
<td>10.7899</td>
<td>74.5295</td>
<td>&lt;.0001****</td>
</tr>
<tr>
<td>Humidity x Temperature</td>
<td>6</td>
<td>6.0653</td>
<td>13.9650</td>
<td>&lt;.0001****</td>
</tr>
<tr>
<td>Spine Color</td>
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<td>0.9551</td>
<td>13.1950</td>
<td>0.0007***</td>
</tr>
<tr>
<td>Humidity x Spine Color</td>
<td>3</td>
<td>0.7327</td>
<td>3.3738</td>
<td>0.0258*</td>
</tr>
<tr>
<td>Temperature x Spine Color</td>
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<td>0.2473</td>
<td>1.7081</td>
<td>0.1920</td>
</tr>
<tr>
<td>Humidity x Temperature x Spine Color</td>
<td>6</td>
<td>1.7545</td>
<td>4.0397</td>
<td>0.0024**</td>
</tr>
</tbody>
</table>
An ANOVA shows significant effects of humidity (P<0.0001), spine color (P=0.0043) and the interaction between humidity x temperature (P<0.0001) on flexural modulus (Table 8.3). The ANOVA corroborates an inverse relationship between flexural modulus and relative humidity for samples conditioned at room temperature. White spines tended to be stiffer (LS-mean = 3.5703 ± 0.0692 N/mm) than multicolored spines (LS-mean = 3.2766 ± 0.0692 N/mm).

Table 8.3. Analysis of variance of the effect of humidity, temperature, spine color, and their interactions on flexural modulus. * P≤0.05; ** P≤0.01; *** P≤0.001 **** P≤0.0001.

<table>
<thead>
<tr>
<th>Source</th>
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<th>SS</th>
<th>F Ratio</th>
<th>P-value</th>
</tr>
</thead>
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<tr>
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<td>13.1597</td>
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</tr>
<tr>
<td>Temperature</td>
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<td>0.1007</td>
<td>0.9044</td>
</tr>
<tr>
<td>Humidity x Temperature</td>
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<td>9.5356</td>
<td>&lt;.0001****</td>
</tr>
<tr>
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<td>1</td>
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<td>8.9915</td>
<td>0.0043**</td>
</tr>
<tr>
<td>Humidity x Spine Color</td>
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<td>0.5878</td>
<td>1.1349</td>
<td>0.3444</td>
</tr>
<tr>
<td>Temperature x Spine Color</td>
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<td>0.8061</td>
<td>2.3348</td>
<td>0.1077</td>
</tr>
<tr>
<td>Humidity x Temperature x Spine Color</td>
<td>6</td>
<td>1.1557</td>
<td>1.1157</td>
<td>0.3674</td>
</tr>
</tbody>
</table>

Specific Stiffness and Strength vs. Conventional Materials

In general, hedgehog spines exhibit lower specific stiffness than carbon fiber rods, 316 stainless steel tubes, 201 stainless steel rods, and nylon 6/6 rods; but greater specific strength than styrene rods, nylon 6/6 rods, and 201 stainless steel rods. Some hedgehog spines conditioned at high temperature and low relative humidity (35-60%) even exhibit greater flexural strength than 316 stainless steel tubes (Figure 8.11). Specific stiffness and strength in conventional materials tend to be linearly related, but hedgehog spines do not follow this model. For a vast majority of temperature and humidity conditioning parameters, hedgehog spines are ounce for ounce stronger than 201 stainless steel but as pliable as styrene. This unique combination of strength and
elasticity makes hedgehog spines exemplary shock absorbers, and a suitable model for bioinspired design of lightweight, material-efficient, impact-resistant structures.

Figure 8.11. Specific stiffness and specific strength of hedgehog spines versus conventional materials. Load-deflection data normalized by specimen weight.

Conclusions

As in previous studies of hedgehog spine arrays (Swift et al., 2016) and other keratinous materials (Chou & Overfelt, 2011), we find an overall inverse correlation between relative humidity and flexural strength of individual hedgehog spines. Relative humidity is also inversely correlated with flexural modulus of spines conditioned at room temperature. Contrary to previous studies of other keratinous materials our data does not reflect an inverse correlation between temperature and flexural strength (Miserez et al., 2009; Papir et al., 1975). Instead, we see a dip in hedgehog spine flexural strength at room temperature (23°C) with greater strength at both high (80°C) and low (1°C) temperatures. Spines conditioned at high temperature (80°C) have numerically higher max loads (N) than spines conditioned at room temperature across all relative humidity treatments. High temperature may induce formation of microfibrils, increasing
material strength and stiffness while decreasing water absorbability. This hypothesis is supported by hygroscopic moisture measurements.

Multicolored spines conditioned at room temperature (23˚C) appear to be more susceptible to humidity effects (decreased flexural strength and modulus with increasing relative humidity) compared to white spines, despite very similar water uptake behavior. ANOVAs show white spines tend to be stronger and stiffer than multicolored spines overall. Future studies characterizing the material properties of dark versus light sections of hedgehog spines, using techniques like nanoindentation and dynamic mechanical spectroscopy, may help explain mechanical differences between multicolored and white spines.

For a vast majority of temperature and humidity conditioning parameters, hedgehog spines are ounce for ounce stronger than 201 stainless steel but as pliable as styrene. This unique combination of strength and elasticity make hedgehog spines exemplary shock absorbers, and an extremely suitable reference model for design of lightweight, material-efficient, impact-resistant structures. Hedgehog spines could inform innovations in personal protective equipment that elevates safety without disrupting the wearer’s balance or causing fatigue; paneling for automotive and aerospace vehicles that is durable and crash-resistant and does not diminish fuel-efficiency; and transport cases for expensive equipment that cushion fragile contents during bumpy transit.
Acknowledgements

The authors would like to express their sincere thanks to Kimberly Goertzen of West Coast Hedgehogs for preparing and donating the hedgehog pelt from which spine samples were collected; Dr. Zhorro (George) Nikolov for micro-CT training and support; Dr. Boyce Collins (ERC-RMB at North Carolina A&T State University) for 3D reconstructions of spines using nano-CT (NSF Award No. 260145); Dr. Peter Niewiarowski for performing ANOVAs; and Christopher Drol and Tyler Yoder for experimental assistance and manuscript proof-reading. This work was supported by the NSF [I-Corps Sites Award No. 1000001693NSF]; and the Lemelson Foundation [VentureWell E-Team Program Grant No. 13859-15]. K.T. Tan also acknowledges the Faculty Start-Up Grant provided by The University of Akron.
CONCLUSION

To accelerate industry adoption of biomimicry, the fog surrounding how it is done and what specific benefits it can offer businesses needs to be lifted. My dissertation begins us on a path to clarity, by detailing a biomimicry process successfully implemented in an industry setting, and revealing a few of what I believe to be many layers of value biomimicry can bring to an organization.

Biomimicry, as successfully implemented at GOJO Industries, generally comprised five phases: 1) Problem definition; 2) Specification of desired functions; 3) Identification of biological models exemplifying desired functions; 4) Extraction of design principles embodied by biological models; and 5) Ideation of biomimetic solutions using design principles as stimuli. There is still so much to be learned about industry best practices for each of these phases. Future work should explore and optimize each in turn. The more efficient and effective we become at leveraging nature’s 3.8 billion years of R&D, the more interest in biomimicry will be generated within industry.

With respect to the value of biomimicry, this collection of works indicates that philosophically, the approach can help us shed our hubris and remember that humans are one of millions of species trying to survive and thrive on Earth. Like other species,
we are subject to Earth’s limits. As Finnish architect Gottlieb Eliel Saarinen once said, “Always design a thing by considering it in its next larger context – a chair in a room, a room in a house, a house in an environment, an environment in a city plan.” Biomimicry helps innovators recall their largest context… the Earth.

Economically, this body of work shows that compared to conventional approaches to front end innovation biomimicry has potential to produce double the intellectual property for a sixth of the personnel and financial resources. Economic and environmental sustainability cannot be decoupled, and our work also demonstrates biomimicry has potential to inform solutions offering double to quadruple the energy savings. To quote a March 17, 2017 FORTUNE Magazine article: “If you’re not incorporating the most brilliant ideas from the natural world into what you sell, you’re leaving money on the table.”

Regarding creativity, we provide evidence that priming innovators with biological analogies increases novelty (originality), and potentially enhances elegance (execution) of product concepts generated versus industrial analogies. Both novelty and elegance are tied to a product’s success in the marketplace. We also strongly suspect, but have not proven, that biomimicry intrinsically motivates new product development practitioners, at least in some business contexts. Intrinsic motivation (i.e. interest, enjoyment, and satisfaction in work itself) is positively correlated with creativity. Future work is necessary to confirm this effect.

Moving forward my goal will be to repackage these academic contributions into a form more readily accessible to businesspeople, and spread the word via face-to-face
interactions as a biomimicry innovation consultant. Industry must overcome its inherent resistance to change, recognize biomimicry’s philosophical, economic, environmental, and creative promise, and pilot the approach within their organizations. I predict industry adopters will see improvements in their triple bottom line and develop technologies that transform the world as we know it.
LITERATURE CITED


Gentner, D., Loewenstein, J., & Thompson, L. (2003). Learning and transfer: A general role for analogical encoding. *Journal of Educational Psychology, 95*(2), 393–408. https://doi.org/10.1037/0022-0663.95.2.393


Gruber, P. (2016, June 29). Most Challenging Aspects of Bioinspired Design [E-mail].


Han, S. H., Yun, M. H., Kim, K.-J., & Kwahk, J. (2000). Evaluation of product usability: development and validation of usability dimensions and design elements based


APPENDICES
Handout 1 (two versions for two search objectives)

Search Objective 1: Search and identify as many biological models for attachment, including temporary attachment and attachment to irregular surfaces, as you can within the allotted 60 minutes. Your search should be guided by the question:

“How do biological models accomplish the desired function(s)?”

<table>
<thead>
<tr>
<th>Biological Model</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Organism, Form, Process, System</strong></td>
<td>How is this biological model relevant to your search objective?</td>
</tr>
</tbody>
</table>

+11 additional rows for 12 rows total

Search Objective 2: Search and identify as many biological models for sealed storage / liquid containment as you can within the allotted 60 minutes. Your search should be guided by the question:

“How do biological models accomplish the desired function(s)?”

<table>
<thead>
<tr>
<th>Biological Model</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Organism, Form, Process, System</strong></td>
<td>How is this biological model relevant to your search objective?</td>
</tr>
</tbody>
</table>

+11 additional rows for 12 rows total
Handout 2 Front Side (two front versions for two search objectives)

Search Objective 1: Search and identify as many biological models for attachment, including temporary attachment and attachment to irregular surfaces, as you can within the allotted 60 minutes. Your search should be guided by the frames of inquiry listed on the reverse side of this handout. Code each biological model according to which frame of inquiry helped lead to its identification.

<table>
<thead>
<tr>
<th>Biological Model</th>
<th>Details</th>
<th>Frame of Inquiry Code</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>(F1, F2, F3, F4)</td>
</tr>
</tbody>
</table>

+11 additional rows for 12 rows total

Search Objective 2: Search and identify as many biological models for sealed storage / liquid containment as you can within the allotted 60 minutes. Your search should be guided by the frames of inquiry listed on the reverse side of this handout. Code each biological model according to which frame of inquiry helped lead to its identification.

<table>
<thead>
<tr>
<th>Biological Model</th>
<th>Details</th>
<th>Frame of Inquiry Code</th>
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</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>(F1, F2, F3, F4)</td>
</tr>
</tbody>
</table>

+11 additional rows for 12 rows total
F1: Similar Context - What biological models exist in a context similar to the problem context in terms of scale of interest, climate, etc.? (This frame assumes biological models inhabiting environments similar to the problem context will adopt strategies that may be relevant to the problem.)

Example: If the desired function was wet adhesion, an innovator adopting a “similar context” frame of inquiry would search and identify models that affix in wet environments (i.e., mussels).

F2: Extremes - What biological models deal with the extreme versions of the problem? (This frame assumes biological models most challenged by the problem will embody the most robust strategies for addressing it.)

Example: If the desired function was stormwater management, an innovator adopting an “extremes” frame of inquiry would search and identify models living in regions with high annual rainfall (i.e., sphagnum moss).

F3: Convergence – What biological strategy for accomplishing the desired function is used by many, distantly related species? (This frame assumes a strategy independently evolved in different contexts is likely to be a beneficial approach.)

Example: If the desired function was location tracking, an innovator adopting a “convergence” frame of inquiry would be particularly interested in sonar-like echolocation, independently evolved by bats, toothed whales, and shrews.

F4: Stasis - What biological strategy for accomplishing the desired function has persisted over time? (This frame assumes a strategy that has been conserved through evolution is likely to be effective and difficult for competitors to defeat.)

Example: If the desired functions were protection and mobility, an innovator adopting a “stasis” frame of inquiry would be particularly interested in the horseshoe crab’s articulating exoskeleton, which has remained morphologically constant for ~450 million years.
Survey 1

1. What is your gender? Check a box.
   □ Male
   □ Female
   □ I prefer not to specify

2. What is your age? Check a box.
   □ 17 years and under
   □ 18-29 years old
   □ 30-49 years old
   □ 50-64 years old
   □ 65 years and over

3. What is the highest level of education you have attained? Check a box.
   □ Some high school
   □ High school graduate
   □ Some college
   □ Trade / technical / vocational training
   □ College graduate
   □ Some postgraduate work
   □ Post graduate degree

4. I earned a college/postgraduate degree(s) in the following subject area(s):

__________________________________________________________________
Leave blank if none.

5. To which search objective was your team assigned?
   □ Search Objective 1 – Search and identify biological models for attachment, including temporary attachment and attachment to irregular surfaces
   □ Search Objective 2 – Search and identify biological models for sealed storage / liquid containment
6. What is your level of familiarity with biomimicry? Circle a number.

Not at all familiar  Slightly familiar  Somewhat familiar  Moderately familiar  Extremely familiar
1  2  3  4  5

7. How difficult did you find this exercise? Circle a number.

Very difficult  Difficult  Neutral  Easy  Very Easy
1  2  3  4  5

Survey 2

Same Qs #1-7 as Survey 1 +

8. What other frames of inquiry (in addition to those provided) might support search and identification of biological models?

__________________________________________________________________
__________________________________________________________________
__________________________________________________________________
## C-CSDS

<table>
<thead>
<tr>
<th>Category</th>
<th>Output Property</th>
<th>Creativity Indicator</th>
<th>Indicate the extent to which the creativity indicator applies to the output you are evaluating.</th>
</tr>
</thead>
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<tr>
<td>Relevance &amp;</td>
<td>The output is fit for purpose.</td>
<td>1. Correctness (the output accurately reflects conventional knowledge and/or techniques)</td>
<td>Not at all A little Somewhat Quite a lot Very Much</td>
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<tr>
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<td></td>
<td>2. Performance (the output does what it is supposed to do)</td>
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<tr>
<td></td>
<td></td>
<td>3. Appropriateness (the output fits within task constraints)</td>
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</tr>
<tr>
<td>Problematization</td>
<td>The output helps to define the problem/task at hand.</td>
<td>4. Diagnosis (the output draws attention to shortcomings in other existing outputs)</td>
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<tr>
<td></td>
<td></td>
<td>5. Prescription (the output shows how existing outputs could be improved)</td>
<td>1 2 3 4 5</td>
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<td></td>
<td></td>
<td>6. Prognosis (the output helps the beholder to anticipate likely effects of changes)</td>
<td>1 2 3 4 5</td>
</tr>
<tr>
<td>Propulsion</td>
<td>The output sheds new light on the problem/task.</td>
<td></td>
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<tr>
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<td>------------------------------------------------</td>
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<tr>
<td></td>
<td>7. Redirection (the output shows how to extend the known in a new direction)</td>
<td></td>
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<tr>
<td></td>
<td>8. Reinitiation (the output indicates a radically new approach)</td>
<td></td>
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<tr>
<td></td>
<td>9. Redefinition (the output helps the beholder see new and different ways of using the output)</td>
<td></td>
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</tr>
<tr>
<td></td>
<td>10. Generation (the output offers a fundamentally new perspective on possible outputs)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Elegance</td>
<td>The output is well-executed.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>11. Convincingness (the beholder sees the output as skillfully executed, well-finished)</td>
<td></td>
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<tr>
<td></td>
<td>12. Pleasingness (the beholder finds the output neat, well done)</td>
<td></td>
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<tr>
<td></td>
<td>13. Completeness (the output is well worked out and “rounded”)</td>
<td></td>
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<tr>
<td></td>
<td>14. Gracefulness (the output is well-proportioned, nicely formed)</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>15. Harmoniousness (the elements of the output fit together in a consistent way)</td>
<td></td>
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</tr>
<tr>
<td>16.</td>
<td>Sustainability (the output is environmentally friendly)</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Genesis</td>
<td>The output changes how the problem/task is understood.</td>
<td></td>
</tr>
<tr>
<td>17.</td>
<td>Foundationality (the output suggests a novel basis for future work)</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>18.</td>
<td>Transferability (the output offers ideas for solving apparently unrelated problems)</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>19.</td>
<td>Germinality (the output suggests new ways of looking at existing problems)</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>20.</td>
<td>Seminality (the output draws attention to previously unnoticed problems)</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>21.</td>
<td>Vision (the output suggests new norms for judging other solutions – existing or new)</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>22.</td>
<td>Pathfinding (the output opens up a new conceptualization of the issues)</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Overall Creativity</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Indicate how creative, overall, the output is.</td>
<td>Not at all</td>
<td>A little</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>2</td>
</tr>
</tbody>
</table>
Figure A.1. Schematic illustration of sample preparation process. (A) A piece of packing foam. (B) Insert spines into the packing foam. (C) Flip the packing foam with spines inserted. (D) Pour freshly prepared substrate (viscous fluid) into assembled mold. (E, F) Insert packing foam with spines into the assembled mold with substrate settled at the bottom of the mold and wait until the substrate cures. (G, H) After the substrate is fully cured, carefully remove the packing foam. (I) Disassemble the mold. (J) Final sample used during crash pendulum impact tests.
Figure A.2. Speed-time curves from high-speed video analysis.

Figure A.3. Acceleration-time curves from high-speed video analysis.
Figure A.4. Typical speed-time curves that are used to calculate the kinetic energy difference before and after collisions,

\[ \varepsilon_{norm} = 1 - \frac{v_{Li}^2}{v_{Rf}^2} \]

where \( v_{Li} \) is the velocity of the left pendulum immediately before the collision, and \( v_{Rf} \) is the velocity of the right pendulum immediately after collision.

Table A.1. Energy absorption and acceleration values extrapolated from high-speed video analysis. Acceleration values are based on the peak of the red curves in Figure A.3. Energy absorption is calculated based on the data from Figure A.2 and using the equation in Figure A.4.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Low Energy</th>
<th>High Energy</th>
<th>Energy absorbed (%)</th>
<th>Acceleration (mm/s²)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1  2  3  4  5</td>
<td>1  2  3  4  5</td>
<td></td>
<td></td>
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<tr>
<td>A</td>
<td>68.85 63.43 55.48 51.79 46.52</td>
<td>54.25 52.65 47.91 48.66 45.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>56.71 62.79 54.93 56.43 52.88</td>
<td>69.39 56.77</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>58.31 54.03 55.16 57.34 53.22</td>
<td>54.14 48.18 45.5 47.14 44.52</td>
<td></td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>65.62 63.74 59.74 60.45 58.54</td>
<td>56.66 49.16 52.88</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>37.20 38.70 41.08 42.74 42.92</td>
<td>55.52 54.85 53.51 53.78 54.33</td>
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<td></td>
</tr>
<tr>
<td>F</td>
<td>39.24 57.45 56.34 55.75 53.91</td>
<td>54.99 59.88 54.03</td>
<td></td>
<td></td>
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<tr>
<td>NoMat</td>
<td>1016 1012 1142 1308 1298</td>
<td>2181 2114 1988 2154 1778</td>
<td></td>
<td>1349 1502</td>
</tr>
<tr>
<td>Foam</td>
<td>867 1107 1237 1041 790</td>
<td>1666 2193 2086 2175 2001</td>
<td></td>
<td>1956 1931</td>
</tr>
<tr>
<td></td>
<td>825 1088 1199 1228 1028</td>
<td>1669 1956 1931 1872 1791</td>
<td></td>
<td>1999 1900 1992</td>
</tr>
<tr>
<td>E</td>
<td>1044 1152 1078 1005 1178</td>
<td>2109 2046 2285</td>
<td></td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>1427 1407 1340 1170 1440</td>
<td>1769 1891 1689</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NoMat</td>
<td>1151 1077 1070 1146 1079</td>
<td>1769 1891 1689</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Foam</td>
<td>1151 1077 1070 1146 1079</td>
<td>1769 1891 1689</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### APPENDIX D

**BIOINSPIRED INTELLECTUAL PROPERTY**

<table>
<thead>
<tr>
<th>Application No. Title</th>
<th>Inventors</th>
<th>Assignee</th>
<th>Bioinspiration</th>
<th>Summary</th>
</tr>
</thead>
<tbody>
<tr>
<td>US20160121351 Double Acting Bladder Pump</td>
<td>Nick Ciavarella, Emily Kennedy</td>
<td>GOJO</td>
<td>Human Heart – a multichambered biological pump with common walls</td>
<td>Like the heart, the double-acting bladder pump has separate elastomeric chambers walled off from each other by a central spine that incorporates fluid inlet and outlet valves. Coupled drive arms are used to actuate the pump. Energy recaptured from the recovery cycle of one chamber helps compress the other chamber.</td>
</tr>
<tr>
<td>Serial 62461258 Universal Dispenser Mounting Brackets</td>
<td>Nick Ciavarella, Seth Glasgow, Stephen Howe, Emily Kennedy</td>
<td>GOJO</td>
<td>Bat – gravitational pull on body weight of an upside-down, roosting bat activates finger clamping (passive); muscle contraction unclenches fingers (active)</td>
<td>A bracket comprised of a base (where the dispenser is mounted) with two spring arms extending in opposite directions. Moving the first and second spring arms away from their rest position generates a clamp force in the spring arms that urges the first and second spring arms toward their rest position. When the mounting bracket is mounted to a surface, the base is on a first side of the surface and the first and second arms are on a second side of the surface. The clamp force generated by the spring arms secures the mounting bracket to the surface.</td>
</tr>
<tr>
<td>PCT/US16/52760 Impact Protection and Shock Absorbing Device</td>
<td>Emily Kennedy, Daphne Fecheyr-Lippens, Bor-Kai Hsiung, Douglas Paige, Nathan Swift</td>
<td>University of Akron</td>
<td>Hedgehog – active climbers that often fall from height; quills projecting from pelts have evolved to absorb shock</td>
<td>Liner consisting of polymer ‘quills’ projecting from a base at varying angles. As in the hedgehog model, when one quill is sufficiently deflected, it strikes adjacent quills, transferring force in a continuing cascade. This enables multidirectional energy dissipation, and thereby, linear and angular acceleration reduction. Synthetic ‘quills’ also have internal structure like hedgehog quills that improves their resilience, increasing the liner’s multi-hit durability.</td>
</tr>
</tbody>
</table>
APPENDIX E

TECH STARTUP FUNDRAISING

Table A.3. Funds awarded to Hedgemon, startup licensing PCT/US16/52760 from University of Akron with intent to commercialize a shock absorbing football helmet liner to reduce risk of concussion.

<table>
<thead>
<tr>
<th>Source</th>
<th>Program</th>
<th>Type</th>
<th>Date</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>NSF</td>
<td>I-Corps Sites</td>
<td>Grant</td>
<td>Feb 2015</td>
<td>$2,500</td>
</tr>
<tr>
<td>Burton D. Morgan Fdn</td>
<td>PITCH U</td>
<td>Cash Prize</td>
<td>Oct 2015</td>
<td>$3,000</td>
</tr>
<tr>
<td>Burton D. Morgan Fdn</td>
<td>Hudson Library Pitch Night</td>
<td>Cash Prize</td>
<td>Nov 2015</td>
<td>$1,500</td>
</tr>
<tr>
<td>Lemelson Fdn</td>
<td>VentureWell E-Teams Stage 1</td>
<td>Grant</td>
<td>Dec 2015</td>
<td>$5,000</td>
</tr>
<tr>
<td>George W. Codrington Charitable Fdn, Fran &amp; Jules Belkin, Brandon Palmer</td>
<td>think[box] Student Project Fund</td>
<td>Grant</td>
<td>Mar 2016</td>
<td>$2,500</td>
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<tr>
<td>Lemelson Fdn</td>
<td>VentureWell E-Teams Stage 2</td>
<td>Grant</td>
<td>Mar 2016</td>
<td>$20,000</td>
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<tr>
<td>Burton D. Morgan Fdn</td>
<td>LaunchTown Business Idea Competition</td>
<td>Cash Prize</td>
<td>Apr 2016</td>
<td>$1,000</td>
</tr>
<tr>
<td>Ohio Development Services Agency</td>
<td>Third Frontier Tech Internship Program</td>
<td>Grant</td>
<td></td>
<td>$10,000</td>
</tr>
<tr>
<td>Rock the Pitch</td>
<td>Kickoff Event</td>
<td>Cash Prize</td>
<td>Oct 2016</td>
<td>$500</td>
</tr>
<tr>
<td>Lorain County Community College Foundation</td>
<td>Innovation Fund A Award</td>
<td>Grant</td>
<td>Nov 2016</td>
<td>$25,000</td>
</tr>
<tr>
<td>VentureWell</td>
<td>Open Minds Showcase</td>
<td>Cash Prize</td>
<td>Apr 2017</td>
<td>$2,000</td>
</tr>
</tbody>
</table>
Table A.4. Hedgemon’s pending grant applications

<table>
<thead>
<tr>
<th>Source</th>
<th>Program</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>NSF</td>
<td>STTR Phase I</td>
<td>$225,000</td>
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<tr>
<td>University of Akron Research Foundation</td>
<td>Spark Fund</td>
<td>$100,000</td>
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