Biology as a Muse:

Exploring the Nature of Biological Information and its Effect on Inspiration for Industrial Designers.

by

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A thesis submitted to
the Faculty of Graduate and Postdoctoral Affairs
in partial fulfillment of the requirements for the degree of

Master of Design

in

Industrial Design

Carleton University
Ottawa, Ontario

Your file Votre référence
ISBN: 978-0-494-87848-4

Our file Notre référence
ISBN: 978-0-494-87848-4

ABSTRACT

This thesis looks at how biological information can be presented to industrial designers to inspire them. Incorporating knowledge from biology into design is a complex interdisciplinary process. The researcher employs a biologically inspired toolkit to help deal with this complexity.

To develop this toolkit this thesis looks at current biologically inspired design methods. Three problem areas emerge from this including 1) problems with information transfer; 2) problems with methodological structure; and 3) problems with information representation. All three areas are in need of development. Although, this thesis's focus is on the third problem of bio-inspired design information representation.

A biologically inspired toolkit is created for industrial designers to interact with. To study this, a retention test, an experience survey, and a design challenge were employed.

The results clearly show a biologically inspired design toolkit is beneficial for use by industrial designers and that it positively effects inspiration levels to render novel design solutions.

Keywords: Biologically Inspired Design, Interdisciplinary, Design Methods, Industrial Design, Innovation, Inspiration

ACKNOWLEDGEMENTS

The author would like to express his appreciation and gratitude to several different parties responsible for enriching the contents and making the completion of this thesis possible. Firstly, gratitude is extended to Professor Overhill from Sheridan Institute of Technology who's guidance and support made it possible to be a part of Carleton's M.Des program and community. Much gratitude and acknowledgement is also extended to Carleton's School of Industrial Design, all the hardworking professors, faculty, and staff, the design students who participated in the study, and especially to Prof. Frankel and Prof. Imbesi who recognized and encouraged the author's potential.

Being accepted with open arms with such reputable institutions such as Georgia Institute of Technology and The Biomimicry Institute was pivotal in setting the course of this thesis in the right direction. Gratitude is expressed to Dr. Yen, Director of Georgia Tech's Center for Biologically Inspired Design and her colleagues Dr. Weissburg and PHd candidate Michael Helms. Being treated as a potential credible contributor to the field was very helpful for initial motivation. Thank you Bryony Schwann, Tim Mcgee, Carl Hastrich and the other helpful associates and biologists at The Biomimicry Institute. Being able to verify assumptions through interviews and informal conversation was very helpful at the beginning stages of research.

Most importantly the author extends acknowledgment and his gratitude to his supervisor, Prof. Hallgrimsson, and co-supervisor, Dr. Jeffrey Dawson; both whom insisted on a high level of work and were very encouraging at every point along the journey. Further gratitude is extended to Prof. Hallgrimsson for sharing his knowledge about design philosophy and the financial support was very much appreciated at the projects end. Having access to Dr. Dawson's biology laboratory, lectures, tools, specimens, and his infinite knowledge allowed the author to gain an invaluable experience of a biologist's world.

Lastly, thank you to Dr. Wehrspann for the indispensable encouragement and structure; and to Mrs. Wehrspann for the fine tooth editing.

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CHAPTER 1

INTRODUCTION

Complex problems within the scope of manufacturing and designing products are in need of novel solutions. Integrating differing schools of thought is widely held to be a strategy to do this successfully. One such emerging interdisciplinary approach teams biology and design together to tackle specific problems that relate to the fields of architecture, engineering, ecology and industrial design. Combining the two disciplines of biology and industrial design is the focus of this thesis, which identifies a need to find common tools that can be a part of a methodology that allows designers to use biological information as a source of design inspiration. Three problem areas were identified that could be explored to help in development of such a methodology. These were: biological information transfer; bio-inspired design methodological structure; and bio-inspired design information representation.

Buchanan (1992) in his paper, "Wicked Problems in Design Thinking," argues that without integration of previously fragmented disciplines there is ".....little hope of sensibly extending knowledge beyond the library or laboratory in order to serve the purpose of enriching human life." This thesis contends that applying an interdisciplinary perspective is the most promising of approaches when dealing with what Buchanan (1992) calls 'wicked design problems'.

The problem of sustainability is inherently interdisciplinary. It requires many areas of expertise as a product moves from beginning to end, concept to waste. Whereas sustainability is of some concern to this thesis, it is not the focus as the research was entirely focused on how to affect interdisciplinary work in the context of biologically inspired design.

Unlike other sustainable research methods in which the negative stimulus is exemplified, biologically inspired design represents a positive framework for students to engage in producing concepts for products, services and systems. Biologically inspired design encourages a positive approach that takes inspiration from nature to find innovative solutions. This can be especially important when problems become complex and overwhelming. It has been shown that designers can be thwarted if they are shown negative stimuli, for example in the context of sustainable design, where an emphasis on environmental outcomes of manufacturing or consumption can be overwhelming. The overarching objective of this thesis is to elucidate a method that uses biological information to inspire innovation for industrial designers. This innovation would affect the design and manufacture of more environmentally friendly, cost-efficient, energy efficient, high functionality or new aesthetic designs.

The field of biologically inspired design is a young field in which the terms biomimicry, biomimetics, and biologically inspired design are used interchangeably. Whereas exploration into this terminology warrants a research study of its own, this thesis will use biologically inspired design for purposes of consistency. The author defines this as a design process that uses inspiration from nature.

There are many examples of biologically inspired design that have proven effective in tackling modern day design problems. Young and Saches (as cited in Benyus, 1997) believe we are on a brink of a biologically inspired materials revolution that will have a significant effect on the way we live. The innovation brought about through such an approach is promising when considering product development. It is strongly felt within the design and scientific community that this field has immense potential to offer innovative ways of solving problems (Bonser & Vincent, 2007). The following examples illustrate, respectively, how biologically inspired design function in the context of an everyday product, a practical research project, as well as ongoing research in academia.

- Product: Velcro, Please see Appendix A
- Project: Design for a Living World, Please see Appendix A
- Research: Center for Biologically Inspired Design, Please see Appendix A

Whereas this is an emerging field, historically the approach of biologically inspired design is much older than its name (Gebeshuber et al., 2009). According to several resources, Jack Steele first coined the term bionics in the early 1950's. Its intention was to describe mechanical systems that function like living organisms. Sometime later in the 1950's Otto Schmitt coined the term biomimetics, a term intended to describe the transfer of ideas and analogues from biology to technology (Vincent et. al, 2006). Janine Benyus is the latest leader of what could be called a movement and a burgeoning discipline. Her book "Biomimicry," first published in 1998, has served as resource for the increasing amount of practitioners to this date. With the increase in research, comes the increase of findings and knowledge. What also comes is the desire to coordinate this knowledge into a coherent discipline for effective practice by its participants.

Biologically inspired design shares the same ailments of other interdisciplinary design efforts. Different backgrounds, knowledge, methods and terminology can make communication between biology and design challenging. Part of the problem Buchanan (1992) states, is that members of the scientific community are puzzled by the types of problems addressed by professional designers and by the patterns of reasoning they employ. Biologists do not think the same way about design as do professional designers. Biologists use their discipline specific knowledge to think about design in the context of evolutionary processes, anatomy, physiology, and constraints. The scientific method can be rigid while the designer's process remains a surprisingly flexible activity (Buchanan, 1992). Clearly there is a culture and information clash between the two disciplines. Development of common tools to communicate and share knowledge is a requirement for successful biologically inspired design ideation.

1.1 Statement of the Problem:

The field of biologically inspired design has great potential to deliver. It is however a rapidly growing and young discipline. As such there is much to be learned. A gap exists to explore the development of a biologically inspired design method. Within this gap the research reveals three interdependent sub-areas in need of elucidation for successful development of this method. These include: 1) biological information transfer; 2) biologically inspired methodological structure or protocol; and 3) biologically inspired information representation. These areas are interdependent on one another. It is the context of the third area 'information representation' that this thesis focuses.

1.1.1 Biological Information Transfer

The amount of applicable biological phenomena poses a significant challenge to the organization and selection of information that is helpful to the practice of biologically inspired design. Language is also a barrier since terminology within biologically inspired design needs clarification in order for practitioners to easily contribute. Designers also struggle to identify appropriate biological phenomena because the language is foreign. This thesis recognizes three basic methods of information transfer that can facilitate the biologically inspired methodology. The first and most desirable method is *direct communication with a biologist*. The second method is to *transcribe biological information into natural language* so that designers do not have to know biology vernacular to conduct an effective search for relevant information. If designers can search a biology corpus by speaking naturally, this can greatly help the process. The third method is *accessing a biological database*. Each method has its pros and cons. Discovering ways to facilitate information transfer will benefit analogical representation for specific design problems. This thesis looks specifically into the nature of biological information and the methods to select and organize it in order to incorporate it into the designers' methodological structure.

1.1.2 Bio-Inspired Design Methodological Structure

This second problem area is concerned with what to do with the information once it has been located and transferred. The contrast between scientific inquiry and the designer's process poses a challenge. Researchers struggle with placement of representation i.e., when should an example of biological phenomena be introduced into the design method? Vincent et al. (2006) recognize that there is no general approach developed for biologically inspired design; however people are attempting to develop these methods by a search for functional analogies to implement at the most effective time. In this thesis the notion of solution-based and problem-based approaches were both examined in the literature review and employed in the study to shed light on the question of a biologically inspired design method. The solution-based approach is when designers are exposed to biological analogies prior to a well-defined design problem. The problem-based approach is when designers are given the well-defined design problem first and then seek out biological analogies for a solution.

1.1.3 Bio-Inspired Design Information Representation

This thesis explores a third problem, namely that biological information, complex at times, must be presented using inspiring mediums to best coax solutions from a predetermined design problem. It is unclear what mediums to use and how best to present information to industrial designers to affect a biologically inspired design method. This is this thesis's main focus. Voltsad (2008) recognizes this problem of information representation stating, ".... necessary biological material is often hidden in technical, scientific paper written for biologists and rarely organized so that it is accessible to design and engineering functions." Once the information is selected and applied to either a problem-based or solution-based approach there is still a question as to how can it be presented to effectively inspire designers? There are three considerations: 1) Text; 2) Visuals; and 3) Objects. This thesis assumes that a multi-modal presentation would be most beneficial. However, it is uncertain in what quantities and in what forms they should take in order to understand the characteristics of a biologically inspired design method that will most effectively inspire designers.

There is an interconnected relationship between biological information transfer, biologically inspired design methodological structure, and biologically inspired design information representation. This research assumes results from each area will further inform the others. Problem area three assumes designers are visual learners in need of tactile experiences. Thus presenting the correct information within a structured methodology using designer friendly mediums is paramount to furthering a biologically inspired design method.

1.2 Purpose of the Study:

The purpose of this thesis is to explore the field of biologically inspired design as it relates to biological information transfer, methodological structure and information representation in the context of interdisciplinary design. The study is conducted with ambitions of adding to a conversation that facilitates the development of a structured method that can serve as a normative process to be adopted by industrial design practitioners.

Through adoption of a biologically inspired design method, industrial designers may find inspiration from previously untouched areas in order to discover innovative solutions for production related problems that affect the environment, economy, and society.

Within the context of the Carleton University setting this thesis utilizes the facilities and knowledge of the School of Industrial Design and the Department of Biology. By utilizing these facilities and their respective resources, a biologically inspired design toolkit was created to test the efficacy of a stand-alone method. By exploring previous research this thesis strives to further knowledge creation in respects to information transfer methods, problem and solution-driven design approaches, and informative mediums such as text, visuals, and objects. Design artifacts and biological artifacts representing problems and solutions were collected and organized as an installation that served as an interactive toolkit undergraduate industrial design students could use. The researcher used furniture design examples to represent a leaping off point for the design students to innovate upon using inspiration from biology. By employing a triangulation strategy including a retention test, an experience survey and a design challenge, knowledge and inspiration levels could be assessed. Development of a toolkit could also be seen as development of a bridge between the two disciplines. See Figure 1. below for a visual model of this concept.

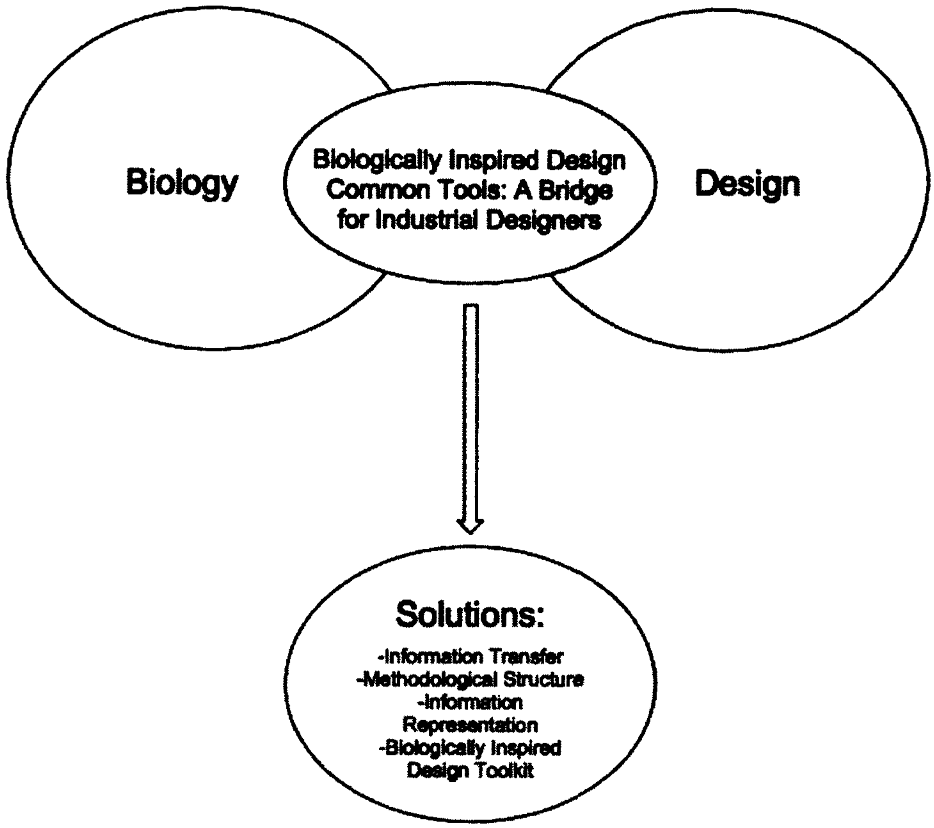

Figure 1. Visual Model of Disciplinary Bridge

1.2.1 Research Questions:

The research questions addressed in the study are:

1. Does a stand-alone installation of biological information inspire designers?

2. Will it inspire them to use inspiration from nature now and in future projects?

3. Is there measurable difference in the level of inspiration and material retention between a 2D *versus* a more tangible 3D installation of artifacts?

The answers to these questions are expected to further inform the development of a biologically inspired design method for use by industrial designers.

1.3 Significance to the Field:

Design students from all disciplines are becoming more aware of biologically inspired design as they realize its value to the development of innovative design ideas. This thesis hopes that it may affect the entire field on some level. Communications were had via phone, email, and face-to-face contact with three North American Institutions that are currently spearheading research into this field. Consulting with the Biomimicry Institute, Georgia Technological Institute, and Ontario College of Art verified the need to proceed with exploration into concepts such as inspiration and information representation as they relate to a biologically inspired design methodology.

1.4 Scope and Limitations:

Interactions with biologist Dr. Jeffery Dawson of Carleton University raised an essential issue when working across disciplines, namely that of information transfer. It was evident that this communication issue was in need of exploring. When the researcher was in discussion with the biologist differing terminology between disciplines became evident. Thus there was the need to create a universal language. This was one factor that spawned the concept of the biologically inspired design toolkit. Access to the Biology Department's resources including its greenhouses and assortment of artifacts was helpful in creating this toolkit.

Furniture design represented the problem space for the primary research, as the author has extensive knowledge on this topic and design students could relate to it easily. Furthermore, the furniture industry could stand to benefit from the innovation brought about by a biologically inspired design process. In Canada alone it is a 4.5 billion dollar industry (Statscan, 2010). It stands to benefit in areas related to aesthetics, function, and manufacturing inside and outside the guise of sustainability. A first iteration of a biologically inspired furniture design toolkit was created to measure how such as tool can help guide and inspire designers towards innovative concept generation with the inclusion of biology. This thesis can reasonably extrapolate the positive affects a biologically inspired toolkit can have on other design challenges where biological inspiration would be applicable.

CHAPTER 2

LITERATURE REVIEW

This thesis aligns itself with Steven Vogel's perspective on biologically inspired design, which is that nature is not ideal but optimizes with what it has in its surroundings (Dawson, 2011). Hundreds of millions of years of an iterative process has led to very fine solutions in the natural world. Tapping into these solutions is only part of the process when generating innovation through biologically inspired design. Strong parallels exist between evolution and the design process. Biology and design are akin to one another. The future of biologically inspired design lies in the challenge of breaking down disciplinary barriers and drawing out and strengthening the similarities so that designers and other practitioners may use common tools within a positive method for innovation.

The relationship between biology and design is an emerging field that is referred to as biologically inspired design. This approach holds great potential for increasing manufacturing capabilities, efficiency and sustainability (Shu, 2011); although it is a field that is in much need of development. Within the general area of a biologically inspired design approach this research identifies three subgroups that encapsulate the problems its development faces. These include the issues of biological information transfer, suitable methodological structure or protocol, and biologically inspired design information representation.

The following literature review will address these three areas mentioned above. In the first section research dealing with how appropriate biological phenomena is to be selected and applied into a solution space will be summarized and critiqued. The second section, reviews research studies that deal with what to do with the biological phenomena once it is selected. Finally, the third section will discuss research related to information representation and its affect on inspiration.

All three areas are clearly related and implementation of the first area directly affects the second and third area (Shu, 2011). Thus, there is an overlapping of concepts that emerge from one study in one area, to another.

2.1 Biological Information Transfer

An article by Shu et al. (2011) entitled "Biologically Inspired Design" gives a detailed account of the biologically inspired design landscape. By starting with a broad picture of current strategies, it is able to effectively explain different methods of information transfer from biology to engineering and design. Citing many leaders in the field, Shu et al. (2011), successfully explain the nature of the information, how to tap into that information, and its benefits and consequences. Being the most recent of studies it is crucial in defining the scope of biologically inspired design and the basic terminologies needed for other researchers to easily understand and thus contribute to the field. As this interdisciplinary field develops, understanding and agreeing upon terminology is pivotal to furthering the field. The thesis recognizes that several terms are used interchangeably for biologically inspired design or biomimetics (Shu et. al, 2011). It also points out the difference between bioengineering and biomechanics and most importantly defines biomimetics as:

> Used in the title paper by Schmitt, and defined as, the 'study of formation, structure, or function of biologically produced substances and materials and biological mechanisms and processes especially for the purpose of synthesizing similar products by artificial mechanisms which mimic natural ones' (Shu et. al, 2011).

Furthermore, the terminology study concludes that biomimetics is synonymous with biologically inspired design, biomimicry, and biomimetic design. These terms are not however defined exactly the same in other literature which is why biologically inspired design was the term used in this thesis. Consider the following definitions:

First is a quote from Janine Benyus, on the definition of the word Biomimicry:

> Where ecology meets agriculture, medicine, materials, energy, computing, and commerce biomimicists are learning that there is more to discover than to invent. They know that nature, imaginative by necessity, has already solved the problems we are struggling to solve. Our challenge is to take these time-tested ideas and echo them in our own lives (Benyus, 1997).

This definition is somewhat broad and too teleological for purposes of this paper. Janine Benyus and the institution she helped found may also revere nature on a scale that is too severe for the intentions of this thesis. Peter Forbes in his book, "The Gecko's Foot." addresses this definition with more emphasis on evolutions' part:

> Biomimicists are trying to copy, or at least to adapt, nature's structures and devices. Seen from a deep biological perspective, you could say that one earthly life form (Homo Sapiens) is trying to copy other earthly life forms (spiders, geckos, butterflies, etc.)... earthly life forms have been copying each other and pretending to be what they are not for hundreds of millions of years (Forbes, 2005).

Steven Vogel quotes Jack Steele, a medical doctor who first coined the word 'bionics' defined it as: "a science of systems whose function is based on living systems, or which have the characteristics of living systems, or which resemble these. He adds, "....a more recent designation is "biomimetics," whose imperatives are explicitly mechanical, composite materials and walking vehicles, for instance." He is also quick to point out that some practitioners or followers of biomimetics commit the crime of "biophilia", in which nature is worshipped and that there is a moral superiority in nature's ways of doing things (Vogel, 2000).

This thesis attempts to avoid making any implications of moral superiority. As such, the most accurate and appropriate definition for the purpose of this thesis is the term biologically inspired design.

Shu et al. (2011) argue that it is crucial to systematically and objectively find the needs of those using biologically inspired design, novices and experts alike. Vincent and Mann (2002) also recognize the need for this systematic transfer. On one hand it could include new biologically inspired design manufacturing processes. An ideal example is that of the drilling method based on the ovipositor of a wood wasp, which employs a reciprocating motion (Shu et al., 2011). The proposed drill is very light and operates on low power and can drill an astounding 1-2m deep (Shu et al., 2011). This example provides biological information that is relatively simple to understand and transfer into a design problem space. This is mainly because it is on the microscopic scale and not on a nano-scale. Albeit exciting examples of biologically inspired design at work, such manufacturing processes are in such infancy they are considered outside the purview of this thesis.

Another major challenge in information transfer is how to recognize and extract relevant biological phenomena (Mak & Shu, 2004) in relation to the design problem at hand. Research in this area is concerned with exploring the nature of that information in order to discover how to best incorporate it into a normative method for industrial designers. Most biologically inspired design products to date such as Velcro have come into existence adventitiously (Vincent & Mann, 2002). Researchers strive to create a method that is as intentional as it is effective. This requires that the appropriate biological information be selected and represented for use by the designer. Given the expansive amount of complicated biological phenomena that could be considered as candidates for the solution space, a method to select and organize the appropriate information is the first step in creating this effective normative process. Shu et al. (2011) and Helms et al. (2009) both assert that there are a number of ways to search for biological phenomena relevant to the design problem. These include:

Asking a biologist.
Creating a biological database.
Using a natural-language search.

2.1.1 Asking a Biologist

According to Shu et al. (2011) the benefit of asking a biologist the benefit is you do not have to search or interpret the relevance and potential application of biological information. Once a biologist is accessed, success is based upon a myriad of communication factors. The primary research within this thesis utilized the method of asking a biologist directly. This approach was made easy due to the accessibility afforded by an academic setting. However, as observed by Shu et al. (2011), accessing a biologist is not always an easy task; for example when practitioners engage in such design activities in private or in a business setting. Working directly with a biologist allows practitioners to give more attention to the application of the relevant biological phenomena. One of the leading organizations in the field, the Biomimicry Institute, offers a service called Biologists at the Design Table to facilitate such needs for the private sector. It has been widely successful in bringing biologically inspired designed products to fruition (Biomimicry Institute, 2010).

2.1.2 Creating a Biological Database

Searching through a database can avoid the need for an expert biologist and can be quite accurate and render very focused results. Relevance can also be maximized because words used for the search are the same words used to enter the information into the database. Building the database is however very time consuming when dealing with an immense amount of information. It also requires some biological knowledge in order to handle the appropriate terminology to achieve successful searches.

The website www.asknature.org is an online biologically inspired design database that is operated by the Biomimicry Institute. It is an effective tool that can be used for information transfer. By asking how nature would do something, for example 'clean', the site will navigate one towards an appropriate biological example.

In Vincent and Mann's article, (2002) "Systematic Technology Transfer from Biology to Engineering," the authors discuss the TRIZ database. This is a Russian system that has been successful in integrating information from many different academic disciplines. It is said to have success because it is in a form accessible to all users (Vincent & Mann, 2002). TRIZ is a database of information organized by function, irrespective of industrial or intellectual boundaries (Vincent & Mann, 2002). TRIZ provides an objective framework to access solutions from disparate technologies and sciences. However, what is recognized is that biological phenomena, at the time this article was written, was only a small part of this database (Vincent & Mann, 2002). Vincent and Mann (2002) contest that the existing TRIZ framework integrates well with novel biological information and should be taken advantage of so engineers can utilize it to produce biologically inspired design ideas. The article gives an overview of the concepts that are important to the functioning of TRIZ in the context of biologically inspired design. They are referred to as "Tools of TRIZ" (Vincent & Mann, 2002). They include i) Function, ii) Contradictions, iii) Ideality, iv) Trends of technical evolution and v) Use of Resources. A short description and relevance to this thesis follows:

Function: This refers to the organization of information by function. It allows one to access solutions and identify the most appropriate ones.

Contradictions: Problems are represented by pairs of conflicting parameters enabling users to find solutions made by earlier inventors that overcame the conflict in question (Vincents & Mann, 2002). For example: an airplane nose cone has to be strong and light.

Ideality: This is the notion that technical and natural systems evolve in predictable ways. Like biological adaptation technology develops towards systems that maximize the good and minimize negative traits (Vincent & Mann, 2002).

Trends of Technical Evolution: This 'tool' represented in the framework of TRIZ represents the most potential for the development of a biologically inspired method. The classical TRIZ system has "eight patterns of evolution of technical systems" (Vincent & Mann, 2002). The system can then recommend possible solutions based on the relevancy of a technical pattern.

The study concludes this tool overview by suggesting that further exploration into nature's evolutionary trends would benefit development of TRIZ trends.

Use of Resources: Vincent and Mann (2002) continue to explain that this system at the crux tries to explain how to get maximum use out of the things that exist "in and around the systems we design." Encouraging designers to effectively use resources for production is a central theme to the TRIZ concept.

As the amount of biological information increases rapidly, opponents to the database approach report that it becomes difficult to maintain such a database (Chiu & Shu, 2004; Vincent & Mann, 2002; Shu et al., 2011). Considerable effort, expertise, and time would be required to keep up with the growth. However, a database method such as TRIZ holds great potential for biologically inspired design. It is a reliable system that has proven successful for technological information transfer for decades. Inclusion of novel biological information would only increase its efficacy to fulfill its duty as an effective tool. As it is clear that it is a tool with much room to grow, it may not be an approach readily available as the level of information and abstraction of such information is in question.

2.1.3 Natural Language Search

Shu et al. (2011) recommend a third option to deal with these challenges i.e. conducting a natural-language search using the example of searching a biology textbook as its corpus. Though it is unclear how novices without such resources would input this information, it suggests using introductory biology course material. The initial source of natural language information is critical (Shu et. al, 2011). This source should be written at a simple level that can be understood by practitioners without experience in biology (Shu, 2011).

Chiu and Shu (2004) in their journal article, "Natural Language Analysis For Biomimetic Design," recognize the natural-language search as successful method to systematically identify biological phenomena for transfer. Biological phenomena are recognized as biological analogies when they are paired with a relevant design problem. These analogies are identified by finding instances of functional keywords that describe the engineering problem in biological knowledge in natural-language format. Chiu and Shu (2004) suggest that searching a lexical database using natural-language would considerably reduce the effort and time in seeking appropriate biological phenomena compared to amassing and creating a database of biological information. They state it is difficult to organize this information and determine its relevance because it is an immense amount of information; it is subjective and requires domain expertise. Central to Chiu and Shu's (2004) article is the use of the tool Wordnet. The researchers realize there is still improvement to be made when locating keywords for searching purposes. The study revolves around the need to identify keywords to render the best quality and most quantity of results. "Wordnet is an electronic lexical database, designed and organized according to current psycholinguistic and computational theories of how humans remember language" (Chiu & Shu, 2004). It is organized based on relationships to other words. Wordnet has two features that successfully organize these relationships. The first approach is the word sense approach, which conducts a search using different meanings of the word. The second approach makes use of a troponym tree which “describes different manners of another verb” (Chiu & Shu, 2004). Using Wordnet, practitioners are able to create searches using keywords that react to how people remember and speak a language. This allows novices to access information without knowing specific domain vernacular. All keywords have synonyms that connect them to biological ideas. This method can save a lot of time and effort and allow non-biologists to access biological phenomena with ease. Chiu and Shu (2004) discuss the advantages and disadvantages to this method, including five steps for the natural-language search. The researchers use the problem of ‘cleaning’ e.g. dirt from clothes. The first step is to identify keywords to seek analogies for cleaning. This work uses verbs for searching. Chiu and Shu (2004) state that they are “.....embodying desired functions into verbs, and search verbs to locate biological forms and behaviors to be used as stimuli.” Once Wordnet identified all the related keywords the selected corpus in this case a biology textbook, could then be searched for matches. These matches would then be stored as a plain text file and entered into a spreadsheet. The intent in this step is to quantitatively determine dominant biological phenomena by measuring how many times matches “....occur within a 50-word window around the keyword” (Chiu & Shu, 2004). This is also referred to as how many times a match is ‘collocated.’ The final step was to analyze the results. Analyzing the most frequently collocated words can be used to capture the dominant biological theme that is associated with each of the troponym keywords.

When searching for keywords Chiu & Shu (2004) noted, “....the troponym feature in Wordnet provided an extensive list of other actions not necessarily included in a synonym list". Troponyms render more keywords than synonyms. The use of more keywords will provide a greater quantity of matches and also create a more varied, rich, and assorted set of matches.

A need exists to apply this type of search to select appropriate biological phenomena and then bring it to the ideation phase for industrial designers. This approach still remains an engineer's tool. This is assumed because of its complexity and its history of not being tested among industrial designers or other practitioners of biologically inspired design.

2.1.4 Summarizing Information Transfer

Three main approaches exist that hold potential for transferring information from biology to the engineering/design field. All three have their benefits and limitations. This thesis assumes that having access to a biologist has considerable advantages versus conducting a natural language search or consulting a database, although accessing a biologist can be difficult. A natural-language search can significantly reduce the expertise necessary to access relevant biological phenomena. On the other hand, creating and maintaining a database can prove very time consuming and knowledge dependent. TRIZ represents an existing framework that can facilitate the biologically inspired design approach if more natural information is integrated into the system for practitioners to access. Whatever the means to the end, the objective is to transfer relevant biological analogies easily to the designer's problem space.

There is also the need to explore how best to select and organize this information in order to benefit the outcome. Chiu and Shu (2004) suggest a natural-language approach supporting creativity by identifying relevant biological phenomena. It is a method that can significantly reduce the effort required for practitioners engaged in the process. Vincent and Mann (2002) suggest the already existing TRIZ framework needs further integration of biological information. Once added, this system offers great potential through its use of tools in identifying relevant data for specific design problems. Most importantly it recognizes the role of biological adaptation and optimization and the similarities technical systems share. Accessing and transferring relevant information is one of the keys to developing a normative method for designers to innovate.

This thesis does recognize other programs or methods that facilitate the act of conceptual design. There is currently development of software that works towards these ends. It is outside the scope of this thesis, however it does have significant relevance. Software programs such as SAPPHIRE, Idea-Inspire, and DANE might benefit from the findings from this thesis. They encapsulate all three areas of this thesis i.e. within one program they gather, structure, and represent biological phenomena for application to design.

Two questions remain after the selection of relevant biological analogies has been made. The following area 'Methodological Structure' examines one of them. Specifically, this area deals with issues such as: how much information should be represented; how long should one be exposed to the information; when should one be exposed to the information within the design process; what details should be given to a design problem to render quality results?

2.2 Bio-Inspired Design Methodological Structure

Spotting inspiring ideas is just the beginning; the focus has to be on how such ideas can be systematically, actively and effectively transferred into a relevant design problem space (Shu et. al, 2011). Two methods to foster this activity are discussed. These are: solution-driven and problem-driven design. A problem-driven approach can be described as such: one starts with a human design problem and then searches for appropriate biological phenomena (Helms et. al, 2009). To help achieve successful transfer it is noted that:

1) a problem be defined sufficiently to enable a meaningful search for biological analogies.

2) high-level complex engineering functions be decomposed into simpler functions to be solved by the biological analogies.

3) when conducting a search using a functional description, a specific solutions should be avoided for as long as possible (Shu et. al, 2011).

A biologically inspired design method is evolving. Nigel Cross's article, "Design Cognition: Results From Protocol and Other Empirical Studies of Design Activity," is pivotal in giving transparency and understanding to current methods of design practice which may help this evolution. Cross's (2004) paper covers three main topics: 1) formulation of problems; 2) generation of solutions; and 3) utilization of design process strategies. The article states that designers often do not define the design problem enough, also known as an 'ill-defined' problem (Cross, 2004); at times designers will treat 'well-defined' problems as the former and change the goals and parameters, which results in having a detrimental affect on the final design product. This leads one to believe that defining the design problem with a proper amount of detail and giving a designer a prescribed amount of room is important to the outcome (Cross, 2004). It is not quite known in what exact quantities, as designers have been observed to jump to solutions before the problem was fully defined. This suggests they were acting in a solution-focused manner i.e. it drove the design decisions, not the details of the design problem. Cross (2004) suggests that ideally designers will 'drift' back and forth so the problem informs the solution and the solution further informs the problem (Cross, 2004).

The study also discusses the concept of 'problem framing' (Cross, 2004). Valkenburg and Dorst (As cited in Cross, 2004) found that too much energy naming activities and defining problem features leads to unsuccessful design outcomes. These findings were also variable between novice and expert designers (Cross, 2004). This further suggests that there is an optimal amount of problem definition contingent on the problem itself and the level of experience of the designers completing the task.

Another important insight in 'solution generation' is that of 'fixation,' as suggested by Jansson and Smith (As cited by Cross, 2004). Fixation could vitiate conceptual design because it can block the designer from considering other 'relevant knowledge' (Cross, 2004). Fixation is not necessarily always a negative thing. Experienced designers may fixate on one solution 'intuitively' knowing its benefits and being tenacious to find a successful solution. The idea of 'intuition' in design is an important concept to this article and to this thesis. It is integral to realize how much structure is necessary for the designers' methodology. Radcliffe and Lee (As cited in Cross, 2004) suggest that designers who follow a structure design protocol have more success; though Cross (2004) suggests that it is still unclear. This leaves questions about what decisions should be made about the succession of methodological protocol. This thesis assumes that designing will never be a scientific methodology and as Akin and Akin (as cited in Cross, 2004) found, scientists go about finding solutions differently than designers. Designers have a sense of what Cross (2004) calls 'opportunism.' Designers tend to deviate from a structure more than other practitioners when searching for solutions. Visser (As cited in Cross, 2004) described this as reducing 'cognitive cost' wherein one structure strategy was dropped when the opportunity for something better came along. It has proven to benefit design outcomes.

Whether it is called 'intuition' or 'opportunism' there is no doubt there is a mystic quality in design that researchers are getting closer to understanding. Important to the research problem in this thesis is how designers may be inspired to have this mystic sudden mental insight (Cross, 2004). Akin and Akin (as cited in Cross, 2004) suggest that creating new 'frames of reference' can facilitate this 'creative leap.' This creative leap, Cross (2004) contests, is not so much a jump over a chasm, but a throwing up of a bridge between the problem and the solution. Akin and Lin (As cited in Cross, 2004) suggest that 'novel design decision' can help build such a bridge. Cross (2004), suggests that if designers changed their attention rapidly between different aspects of the task, 6 out of 8 designers produced novel design ideas.

In the context of biologically inspired design, concepts such as problem and solution focused behavior emerged as relevant to understanding how designers become inspired. Solution-focused behavior seems to have drawbacks. Designers seem to naturally seek solutions first. This can lead to positive and negative forms of 'fixation', which affect design outcomes. When problems are being defined it is crucial to allocate the correct amount of information to the designers' problem space and give appropriate parameters to obtain the best outcome. If designers can move from sketching, to idea generation, to modeling in rapid succession it seems novel ideas are generated more frequently. 'Sudden mental insight' is desirable and still mostly unexplainable. Though allowing designers to 'drift' between the solution and the problem and facilitating 'opportunistic' and 'intuitive' design practice will benefit the method. In Helms et. al (2009) article, "Biologically Inspired Design: Process and Products," it is shown how the Center for Biologically Inspired Design (CBID) is able to bring Cross's insights into the context of biologically inspired design.

A problem-based approach is when the human design problem is introduced first and then possible analogies from biology to inspire solutions are introduced second. Solution-based is that process in reverse. Helms et. al (2009) reinforce the need for problem-based methodological development by demonstrating that by applying the right level of detail, and given an appropriate amount of 'filtered clues', the designer will retrieve useful biological information to solve engineering problems successfully. Thus, CBID is putting considerable effort into understanding the nuances of problem/solution-based methodology. The Biomimicry Institute incorporates a solution-based methodology with its workshop, Biologist at the Design Table (The Biomimicry Institute, 2011). Biologists use their expert knowledge to guide design decisions for independent business interests. It begins with expert knowledge and then 'travels' to the problem.

Helms et al. (2009) discusses how biologically inspired design uses analogous phenomena to develop solutions for engineering problems. Using this approach to design is challenging because biologists and engineers speak a different language, have different perspectives on design, deal with different constraints on design problems, and have different resources for realizing an abstract design (Helms et al., 2009). They applied descriptive accounts to capture the cognitive processes designers went through during the practice of biologically inspired design. With what the researchers stated was 'limited intervention' they were able to take detailed accounts of the designer's cognitive process to distinguish mechanisms that would help or hinder the biologically inspired design method. Researchers at Georgia Institute of Technology observed a project-based learning class in which students in teams of 4-5 performed both approaches to biologically inspired design to analyze biological design principles and rationalization of engineering designs. The study aimed to understand biologically inspired design and to identify opportunities for betterment of an effective method for "......biologically inspired design at large" (Helms et al., 2009).

Helms et al. (2009) detail the steps of problem-driven biologically inspired design process: 1) problem definition; 2) reframe the problem; 3) biological solution search; 4) define biological solution 5) principle extraction; 6) principle application. In terms of a solution-based process the steps would be: 1) biological solution identification; 2) define the biological solution 3) principle extraction; 4) reframe the solution; 5) problem search; 6) problem definition; 7) principle application.

Helms et al. (2009) noted four types of errors that occurred while participants were engaged in biologically inspired design that are important to this thesis. These are: 1) oversimplification of complex functions; 2) solution fixation; 3) misapplied analogies and 4) improper analogical transfer. Oversimplification can lead to misinterpretation and thus undesired design consequences. Though this thesis assumes that over complex information can be hurtful to a biologically inspired design method also. Fixation is a common concern of many different researchers. This thesis intends to limit solution fixation in the development of a method to foster successful design outcomes. Misapplied analogies can cause undesired results but it may also allow for serendipitous discovery. Improper analogical transfer can have the same affect.

Helms et al. (2009) noted these interesting trends that may facilitate avoidance of these undesirable errors:

Four of nine projects were solution-based even though experts emphasized the problem-based approach.

Students locked in to a solution and fixated on it even when they were looking for additional sources for inspiration. I.e. once a biological solution is selected, that solution constrains the rest of the design process (Helms et al., 2009).

Some designers noted that there were too many solutions relevant to their problem. Other designers stated the exact opposite. In the most extreme case they reported no relevant biological phenomena.

Helms et al. had several observations significant to this thesis: 1) designers use two different distinct starting points for biologically inspired design; 2) regular patterns of practice emerge in biologically inspired design; and 3) certain errors occur regularly in the design process (Helms et al. 2009). Effective biologically inspired design is characterized by problem specification at the right level of abstraction i.e. knowing enough about a certain human design problem before reaching for biological principles so the designer can retrieve useful biological information. Multi-modal presentation of information also proved to be helpful during biologically inspired design. It was noted that during solution-based practice designers would often fixate on a solution and thus lack flexibility to find other significant information. One participant was quoted stating, 'we've invested too much time in our biological source of inspiration to abandon it now.'

There exists a need to apply a similar study using principles of problem-based and solution-based biologically inspired design for industrial designers. This thesis employs similar approaches developed by the CBID to explore how it may apply to non-engineers.

Helms et al. (2009) details challenges a biologically inspired design process faces once biological analogies have already been extracted and moved to the design space. As the sample groups within this study were truly interdisciplinary, the source of biological information was introduced into the process through an internal source. Once again direct access to a biologist circumvents the need to conduct a natural-language search or consult a database. This thesis seeks to explore the nature of the methods and focus on the challenges it faces such as fixation and the question of information complexity.

One of the challenges with any design method is how to best foster creativity. Benami and Jin (2002) in the article, "Creative Stimulation in Conceptual Design," ask the question; how do designers react to different analogical conceptual stimuli? To better understand some of the queries of area two and methodological structure it may be beneficial "....to capture the relationship between the properties that stimulate cognitive processes and the design operations that facilitate cognitive processes" (Benami & Jin, 2002). This study suggests conceptual design is a process of creating functions, forms and behaviors. Furthermore, Benami and Jin (2002) believe cognitive processes are used in the development of new ideas but conventional methods do not take human cognition into account. If it is conceivable that one could determine how cognitive processes are stimulated, then more effective conceptual design methods could be developed. Benami and Jin (2002) attempt to do this by "....investigating how patterns of creativity can be infused into the process to produce creative ideas" (Benami & Jin, 2002).

Benami and Jin (2002) developed a model to evaluate the relationship between the components of cognitive processes and design operations to measure creativity in conceptual design. They then evaluated the model by protocol analysis of design sessions to confirm its legitimacy. Once the model was confirmed, they conducted a stimulation experiment involving 10 senior level mechanical engineering students. They were given four different types of stimulation: 1) function stimulation; 2) form stimulation; 3) behavior stimulation; and 4) knowledge entity stimulation. The designs were then evaluated by experts to evaluate the quantity and originality of the ideas.

Benami and Jin's (2002) article is important because it deals with the question of 'where' in the methodological structure should the 'entity' or stimuli be placed to best inspire creativity that makes it fitting to analyze this article in problem area two. Benami and Jin (2002) describe 'design operations.' In Benami and Jin's (2002) words, this thesis explores how to manipulate analogy as stimuli ('design entities') to affect these types of design operations. Benami and Jin (2002) discuss two main types of design operations. Internal operations are the inner thoughts designers have to make decisions and external operations are the ways they communicate those thoughts back to themselves and others. Within these two design operations the study intended to expose engineers to design entities and evaluate the 'cognitive patterns' through protocol analysis. Benami and Jin (2002) attempted to document these patterns by coding and measuring their frequency to make conclusions about 'patterns of stimulation.'

The origins of creativity are the creative properties that stimulate idea generation and exploration. Benami and Jin (2002) show how patterns of creativity can be infused into the process to produce creative ideas by injecting different stimuli. If the patterns of stimulation could be further understood, the environment in which people design and the selection of the 'entities' could be better informed. One pattern recognized is how designers react to 'short-distance analogies' versus 'long-distance analogies.' This refers to the relevance of information between biological analogy and the target design problem. Short-distance analogies rendered a higher quantity of ideas while its counterpart rendered more original ideas. It seems that when creating an environment for designers there could be some control using this specific pattern to develop a lot of ideas or original ideas. Benami and Jin (2002) also discuss the concept of fixation. Participants within the study became fixated on the given design problems but were able to broaden their solution when given the appropriate stimuli. It would seem that movement from problem to solution and back is important. The concept of 'drifting' (Cross, 2004) comes to mind. Ultimately Benami and Jin (2002) point out the stimuli should be meaningful, relevant, and ambiguous i.e. long-distance analogies, to inspire novel design solutions.

A need exists to apply this model to a different sample group, i.e. industrial designers. The industrial design process is less rigid than an engineers' and the field could stand to benefit from application of such an approach. Simplification of the method through application of natural behavior analysis may indeed have similar or further findings to lead us closer to the root of the enigmatic characteristics of creativity.

Wherein Benami and Jin (2002) attempt to locate patterns in an attempt to create what this thesis assumes is too much structure, Cross (2004) raises an important point for the methods development of this thesis i.e. structure shouldn't be too structured. Cross (2004) points out the concept of 'opportunism' and its benefit to the designer's process. As designers toe the line in between engineers and artists, a method, which encourages serendipitous findings within a semi-structure, seems appropriate. Designers do benefit from a well thought out protocol. The iterative approach comes to mind in which a cyclical process of prototyping, testing, analyzing, and refining an idea is applied. Allowing designers to move freely inside this structure seems integral. A biologically inspired method should facilitate this flexible structure.

Problem-based approaches are more practiced than solution-based approaches. At the Center for Biologically Inspired Design (CBID), the design process requires that a problem must be defined appropriately before moving into a solution space. 'Well-defined' problems become critical to locating relevant solutions (Cross, 2004). This leads one to believe that defining the design problem with a proper amount of detail and giving a designer a prescribed amount of room is important to the outcome. This will allow the right level of flexibility for designers to be opportunistic. This flexibility can be applied in a solution-based methodology also. This thesis assumes that a mix between problem and solution-based approaches should be applied towards the development of a biologically inspired design method. The main concerns are to avoid fixation, create opportunity, employ a mix of long and short distance analogies, embrace flexibility, introduce semi-complex information, and allow designers to drift between design entities. Untouched within this area is the original notion of environmental fixation in which designers can 'clam-up' when shown negative environmental stimuli. Thus solution-space should withhold a wide variety of information that is 'positive' in nature to help deter designer fixation. Cross (2004) suggests that what should be presented to designers in a biologically inspired design method is a 'problem-solution pair.' Ideally designers will drift back and forth so the problem informs the solution and the solution further informs the problem. This would allow for 'opportunity' and what Benami and Jin (2002) refer to as solicitation of productive 'design patterns.'

2.3 Bio-Inspired Design Information Representation

Industrial designers attain inspiration from many different types of resources. These can include books, academic resources, physical objects, art, Internet resources and so on. As this research is attempting to develop a more successful biologically inspired design method, it is crucial to see how industrial designers react to different resource mediums or stimuli. The most basic categorization of these mediums is the separation of the two-dimensional and three-dimensional. It is unclear which or in what combination will most effectively inspire the designer's process. One assumption is that multi-modal representation of biological phenomena will inspire designers to create more novel design. This includes information in text, visual, and 'hardware' form (Brereton & McGarry, 2000).

In this area three articles are discussed in hopes to further expose the gaps in the field and further inform the primary research undertaken in chapter 3 of this thesis. These three articles look at the use of text, visuals, and physical objects to see how these mediums in combination or individually inspire a designer's process. From this literature review in area three and the primary research experiment conducted, there is hope that findings will further inform the use of biology in the industrial designer's process.

Goldschmidt and Sever's (2010) article "Inspiring design ideas with texts," hails from the Faculty of Architecture and Town Planning, Technichon, Israel Institute of Technology. The researchers make a case for the use of text as a stimulus when inspiring original and practical design. The overarching argument is that "....stimuli in the form of texts presented to student-designers along with a design problem, would improve the quality of their design solution" (Goldschmidt & Sever, 2010). The case for visual stimuli is clear. Designers have long used it for starting and reference points to bring novelty to their solutions. Casakin and Goldschmidt (As cited in Goldschmidt & Sever, 2010) state, "....design research has demonstrated empirically that exposure to visual stimuli at the conceptual stage is beneficial." Much is empirically documented about the effects of visual stimuli. This study looks closely at text to see how it can benefit from further exploration. If so, what type of text is more beneficial to the design process?

Goldschmidt and Sever (2010) give ontological basis for visual stimuli research and provide a few concepts including Finke's (As citied in Goldschmidt & Sever, 2010) 'mental synthesis', which explains that experienced designers achieve better results when sketching. Also worth mentioning is Casakin's studies (As cited in Goldschmidt & Sever, 2010) in which 3 out of 4 designers achieved better designs with visual stimuli versus no visual stimuli. In the same study they found the addition of text to the visual stimuli did not a have a negative affect. Goldschmidt and Smolkov (As cited in Goldschmidt & Sever, 2010) bring forth important information that suggests the type of design problem and whether the designer is a novice or expert, is significant to the type of stimuli used. This suggests that a biologically inspired design method tested with student designers will make use of different representation modalities compared to a method developed for professionals. Goldschmidt and Sever (2010) suggest 'rich stimuli' (Goldschmidt & Sever, 2010) affected originality more than practicality, and that not all stimuli have a positive evocation. The concept of 'fixation' again comes to mind.

Goldschmidt and Sever (2010) suggest that a textual stimulus increases successful design activity. The researchers explain a two-part concept phase: 1) where visual concepts cannot be explained words can express; and 2) the contemplation of words and phrases provides a wider manipulation space in the process of translation into visual images (Goldschmidt & Sever, 2010). The experiment conducted in this study makes use of two kinds of text. The first is closely related to the design problem and the second is unrelated to the design problem. The goal was to see if both kinds could serve as useful stimuli. This can be compared to Benami and Jin's (2002) use of short and long distance analogies.

Within Goldschmidt and Sever's (2010) study, thirty-five industrial design students participated in 3 design tasks with differing stimuli. In each task the participant was asked to design a table and a clock. The first condition had no stimuli, the second condition had related text stimuli, and the third condition had unrelated text stimuli. Each task was allotted a time of 40 minutes. Experts that were naive and blind to the goals of the exercise judged the originality and practicality. They also presided from outside the academic institution that served as the setting for the experiment. Questions are raised about the learning the participants would experience as they moved through each condition. This may in fact alter the results. Another issue worth mentioning is that the judges each graded one-third of the concepts. Each third of the outcome is then sensitive to the biases of the judge.

Findings show that there is no mean difference in the practicality scores between the 3 conditions noted above. However, the scores for originality were considerably higher in the task where textual stimuli, related and unrelated, were present. For the final research question, Goldschmidt & Sever (2010) concluded "....that the two types of text are equally effective in enhancing design creativity, as compared to design without text. There was no obvious difference between the two years of study that represented the participants. The assumption of this thesis is that the spread is not large enough between the experiences of the participants to make a noticeable difference in the results. Goldschmidt & Sever's (2010) findings may be a prudent framework to use as compass for future development of a design methodology wherein novice and expert designers need different stimuli.

How then will text play a role in the development of a biologically inspired design method? There are obvious results from this study to apply. There is still much to be desired in the context of originality and quality of the textual stimulus. This paper assumes that novice designers can benefit from 'traditional' stimuli whereas experts rely more on novel stimuli to produce original ideas. This is where the problem of area 1 plays a large role. If the textual stimuli is novel--which applies well to the increase in biological discovery--no matter if one is a novice or an expert it will benefit the design process. As this previously reviewed study suggests, it may not even matter if the text is related to the visuals or not. This strengthens the case for use of long-distance analogies as stimuli in a biologically inspired design method as discussed by Benami and Jin (2004) in the previous section.

Keller's (2007) journal article offers a unique look into how designers use visual material for inspiration in their process. Using several methodologies researchers at Delft University of Technology, within their ID-StudioLab, developed a research tool to help answer two questions at the heart of the research: 1) how do designers currently collect visual material for inspiration; and 2) how can new media support this? Keller (2007) works on the assumption that visual stimuli are an important source of inspiration to a designer's process. What is significant to this thesis is how best to arrange visual stimuli to facilitate successful conceptual design.

Keller (2007) employed what they called 'research through design approach.' Because the researchers were looking into current situations of the design process and future possibilities, a mixed methods approach was employed. After conducting a preliminary literature review the researchers employed methods of theoretic explorations, ethnographic observations, interaction design explorations, usability experiments, and action research through working prototypes (Keller, 2007). At the beginning of the project design experts were gathered to create a 'theoretical framework' (Keller, 2007) which would be the start of a working prototype and would be placed in a professional design environment to evaluate the use of visual material. A working prototype called 'Cabinet' was put in a designer work practice for three months. The experiment was set up as action research, "....aimed to research the effect of new tools and the new uses they can generate" (Keller, 2007).

Key observations made in Keller's (2007) article are significant to this thesis. As Keller (2007) reiterates, "...designers really surround themselves with a rich collection of physical visual materials." Also through a contextual inquiry within a professional design environment the research noted 6 considerations for tool support in gathering and using visual material. These include: active collecting, merger of physical and digital worlds, visual interaction, serendipitous encounters, breaking rhythm, involving the body, and social aspects of visual material (Keller, 2007).

The 'Cabinet' system, is a table-sized area of interaction with an overhead projection and grabbing system to locate, arrange and store visual media. The developed system could then be placed in a professional design environment to gather further data on how "....new media could influence the role of visual material in the design process" (Keller, 2007). In conclusion, Keller (2007) states that physical and digital visual material has a blurred boundary, and that collecting visual images is a continuous and significant activity for inspiration in the designer's process.

The hope is that Keller's (2007) study illuminates the possibility of using visuals within a biologically inspired design method. Digital visual representation is not of the same concern as physical representation at this point in development of such a method, although a program like 'Cabinet' may reveal important results that would affect the proposal of a biologically inspired design method in the years to come. What seems important is that designers have some control over the arrangement and their interaction with it. As Keller's (2007) study suggests, sitting at a computer flipping through images, no matter how vibrant and communicative they are, does not look like the future of any design process. Things like active collecting, chance encounters, and body movement are important to the development of a design method that renders highly conceptual design products.

This thesis assumes that the same principals could be applied to the use of objects in a designer's method. Brereton and Mcgarry's (2000) journal article, "An Observational Study of How Objects Support Engineering Design Thinking and Communication: Implications for the design of tangible Media," take a close look at the objects and the properties that make this possible. People are adept at reading and interacting with objects, "....many of which we would only encounter once" (Brereton & McGarry, 2000). The main concept behind Brereton and McGarry's (2000) study is that due to movement into a computer age and the resulting focus on human-computer interaction, little is known about how designers benefit from interaction with physical models. Brereton and McGarry (2000) defined physical models as 'hardware.' This refers collectively to physical objects and physical prototyping materials. The article studied groups of engineers to ultimately find out what roles 'hardware' play in supporting design thinking. Brereton and McGarry (2000) state their objective is to facilitate the design of tangible interfaces that employ the best lessons learned from 'hardware' interaction and human-computer interaction.

Brereton and McGarry's (2000) intervention was exploratory in nature. Engineers participated in a design problem that was videotaped using one camera in one spot with a microphone attached. Only routine practices were used as data to analyze. An interdisciplinary team of experts including an engineer, a linguist, a computer scientist, a sociologist and an anthropologist documented these routine practices. This method was adopted because the researchers felt the exploratory nature would capture integral information from this 'natural activity,' versus an experiment conducted in a controlled setting (Brereton & McGarry, 2000). The design problem the engineers were working on was a focused and small-in-scope exercise that was part of a larger multi-year study in which "....engineering students and professional designers were engaging in design project work.....to investigate how engineers learn through designing" (Brereton & McGarry, 2000). The actual design problem was a 40-minute session in which three students were videotaped and observed designing a concept of a mechanism for a kitchen weighing scale.

The study's main observation is that, when they can, design students will use objects to interpret and communicate concepts when possible. Brereton & McGarry (2000) suggest that participants are 'active and opportunistic' in soliciting objects for design activity. This coincides with Cross's (2004) observation of facilitating opportunism. The study states that, "....the fundamental finding of our inquiry is that design thinking is heavily dependent upon experiences with physical objects and materials as evidenced by the frequent references in design conversation" (Brereton & McGarry, 2000). The 'design conversations' mean the language the students were using while participating in the design problem activity. As the study does give examples of these references, like the literature review, they too are not exhaustive. One would think that these references could have been compared to other material on the subject or in some sense have been quantified and visually represented to add credibility to the method employed in Brereton and McGarry's (2000) study. The findings however do offer interesting ideas about the roles the objects play. 'Hardware' is compelling because we can use more than one sense. Brereton and McGarry (2000) state that it also gives physical presence to conceptual models, provokes exploration because it may behave in unpredictable ways, and can reveal the properties and limits of an object. Brereton and McGarry (2000) concluded that there are 9 roles physical objects play in facilitating design thinking and communication. They are listed in Table 1 below.

Table 1. The Roles of Physical Objects and Prototyping Materials in Supporting Design Thinking and Communication (Brereton and Mcgarry, 2000)

Hardware as a Starting Point	**Hardware as Prompt**
Hardware as Chameleon	**Hardware as a Medium for Integration**
Hardware as Thinking Prop	**Hardware as a Communication Medium**
Hardware as an Episodic Memory Trigger	**Hardware as Adversary**
Hardware as Embodiment of Abstract Concepts	

This helps to illuminate certain concepts and justifications for developing a biologically inspired design method that may have a repository of physical objects for designers to interact with. In examining the roles listed above, there are several desirable concepts that could benefit this thesis's research objectives.

Brereton and McGarry (2000) also focus on the application of this knowledge to CAD. As it is not an immediate concern of this thesis for obvious reasons, it does not have significant immediate ramifications. However, interesting to the long term goal of developing a biologically inspired design CAD method--something that is in development by other researchers and mentioned in the first area of this chapter, e.g. SAPPHIRE--is the recommendation that a successful CAD interface would have properties endowed by the roles physical objects play. The most important properties are fluid interpretation and ambiguity objects promote and provoke. "This suggests that there is some in-between ground to be explored for tangible prototyping interfaces" (Brereton & McGarry, 2000).

Tangible objects, text, and visuals play a vital role for inspiration in the designer's process. This research assumes that a multi-modal presentation of all three will be the most successful stimulus. Though it is unclear what the most successful multi-modal mix would be. The previous articles explore the nature of all three mediums to bring us closer to understanding how designers react to these stimuli. Understanding in what proportion these mediums should be represented and with what amount of 'richness' (Brereton & McGarry, 2000) the information should be in is important. If for example the intervention conducted for this thesis involves participants with differing experience, the text presented should be neither too simple nor too complex. As there are relative novice and 'expert' designers within the sample group it is important that the novice designers are not overwhelmed but that the more experienced designers have enough information. Avoiding any form of negative fixation is also important. This can be facilitated by exposing designers to a large group of solutions with relatively simple information. This is so they do not become fixated and interpretations are open to ambiguity. The solution space should remain open and not too focused. This is achievable through the right level of complexity in textual representation (Goldschmidt & Sever, 2010).

Designers rely heavily on an assortment of visuals for inspiration. Keller's (2007) study gives reason that collection of visual material is a continuous activity undertaken by designers. The type of interaction in and about these materials is also significant. This study suggests that designers should have control over the interaction in the context of the arrangement and their own body movement and movement of visuals. Keller (2007) also notes that visual interaction, serendipitous encounters, and breaking rhythm have implications also.

The most significant conclusion from Brereton's and McGarry's (2000) article is that tangible objects provoke novel design thinking. 'Hardware,' as the study refers to it, has 9 different roles to play within the designer's process as mentioned in the table above. Four of these are recognized as significant to the application of this thesis. Objects can act as a prompt to educate a designer on 'key operational parameters' (Brereton's & McGarry's, 2000). Objects are also easily touched and seen, acting as a good basis for comparison. As Keller (2007) suggests body movement has implications and objects can be a 'thinking prop' used as a gestural aid to support thinking (Brereton and McGarry, 2000). The last significant role of objects noted here is that of 'hardware as an episodic memory trigger' i.e. experience with objects serve as a memory device.

The concepts involving text, visual, and tangible representation of information is integral to the goals of this thesis. It is noticed that a fine balance is necessary. The researcher hopes to use these findings to create a method that stands on firm ontological grounds. Furthermore, from this review of literature the researcher recognizes that a biologically inspired design method must not overwhelm a designer to avoid fixation and provide different mediums in different quantities and complexity. This thesis hopes to further illuminate the relationship between these three mediums and the industrial designer's design process.

2.4 Final Research Synthesis

The articles analyzed in the three areas of this literature review effectively cover the scope of the larger researchable problem i.e. development of a positive and normative biologically inspired design method for use by industrial designers. This development depends on further exploration methods of biological information transfer, bio-inspired design methodological structure, and bio-inspired design information representation. It is recognized that each of these areas are intertwined and interconnected wherein findings in one area implicate another. This interconnectedness and the resulting exploration is not linear in nature. However, as humans have for many years, categorizing and isolating these areas help to bring clarity to the objectives of the research. As such, certain decisions have been made about areas one and two to effectively isolate area three for effective exploration. Areas one and two revealed important grounds to base the design of the research methods to be employed in this thesis. These methods will primarily deal with the specific researchable problem in area three.

Area one discusses three different methods to select relevant biological phenomena to apply within the design process, consulting a biologist, conducting a natural-language search, and consulting a database. As a matter of convenience working directly with a biologist was the method used to select relevant biological information to be used to develop the biologically inspired design method. The second decision was that an open problem-space and solution space, i.e. one that offers a variety of analogies and 'not to complex' information, should be represented in the potential method. The reason being is that designers could then avoid some level of fixation, entertain ambiguous thought, 'drift' between solution stimuli and problem stimuli that Cross (2004) contends creates opportunism.' This and using what Benami and Jin (2002) call 'short-distance' analogy should best foster inspiration for a range of design experience. This method would fall somewhere in between 'ill-defined' and 'well-defined' (Cross, 2004). Again, a fine balance is sought to create a method wherein designers sensitivity to stimuli is maximized through manipulation of the methodological protocol structure.

Lastly it is important that visuals surround designers. They should be able to interact with these visuals so they can physically move and 'break rhythm' to increase the chances of serendipitous interactions (Keller, 2007). Brereton and McGarry (2000) state 9 roles objects play with increasing levels of inspiration, four of which this research seeks to apply. An observation relevant to these roles is the outcome of use of multiple objects. It allows designers to rapidly move their focus from one hardware 'prompt' to another (Brereton's and McGarry's, 2000). This seems similar to Keller's notion of breaking rhythm. Both of these concepts lend themselves to Cross's notions of 'intuitive' design and the creation of 'opportunism'. The design process is not rigid; however structure places a part. Learning from what the community currently practices is integral to making a credible contribution to the field. Thus, developing a novel biologically inspired design method for industrial designers using concepts previously discussed will greatly increase those chances.

CHAPTER 3

METHODS

The previous literature review and research synthesis has highlighted factors that the researcher has determined integral to the successful development of a normative biologically inspired design method. The ontological grounds were defined from the literature review to explore the overarching objective of this thesis in order to elucidate a method that uses biologically inspired design to inspire innovation for industrial designers.

The development of the methods evolved through three phases of work. Phase one and two were fact-finding missions as opposed to data collection exercises. Phase one utilized investigative field research that included informal exploratory interviews and conversations to help define terminology, give justification to the research problem and investigate methods. Phase two was also exploratory in nature. The researcher conducted interdisciplinary design discovery with a biologist. Notes were taken during discussions and during visits to a biology laboratory and a formal lecture at Carleton University. Phase three utilized the accumulated findings from the earlier exploratory phases employed and was focused on the specific problem of information representation. Furthermore, phase three is conducted with qualitative and quantitative data collection. The three phases are discussed in detail below.

3.1 Phase 1 - Investigative Field Research

In the literature review three champion North American institutions were identified that were actively participating in biologically inspired design research. As a researcher it was important to consult and learn more from these institutions to further define the researchable questions. The discussions focused on the areas of biologically inspired design terminology, biological phenomena, and methodology with the primary goal of revealing the most prevalent definitions, information, and practices utilized within the field to further guide development of the research methodology. The centers included Georgia Tech with the Center for Biologically Inspired Design (CBID) and the Biomimicry Institute in Montana. Further conversations were had over the telephone with Professor Carl Hastrich, a Biomimicry Institute consultant from the Ontario College of Art and Design (OCAD). Probing questions were established before and during the expert meetings (See Appendix B for the oral interview). It was important for the design of the research strategy to gather information that was wide in scope. There were questions to be answered but it was also evident that there were further questions to develop. To this effect this phase aimed to identify common threads in the field in respect to applications, terminology, and teaching methodologies of biologically inspired design. One area that had emerged as a special area of focus was the use of a toolkit of biological artifacts to try to inspire designers.

Interviews and discussions at the CBID were completed with the director, Dr. Jeanette Yen, as well as the co-director, Dr. Mark Weissburg, Ph.D. student, Michael Helms, and Professor Jim Budd, chair of the industrial design program. This included three different sessions for approximately an hour each. The first session was an individual interview with Prof. Yen in which the questions in Appendix B were used again was a rough guideline. The second session was a group discussion with Dr. Yen, Dr. Weissburg, and Michael Helms. The last session was with Professor Budd and Dr. Yen that took place during a class of biology and engineering students conducting biologically inspired design exercises. Observations were made and collected through note taking.

Interviews and discussion at The Biomimicry Institute, in Montana, were completed with Executive Director Bryony Schwan, Senior Biologist at the Design Table Tim McGee, Biologist at the Design Table Sherry Ritter, and Megan Schknecht, Director of University Education and Relations. As with the experts at the CBID, the probing in the oral interview was used as a rough framework to structure the interview. Interviews took place within 15-30 minute time slots. Each expert was interviewed separately. Notes were taken to collect observations.

The expert interviews in Phase one were part of an emergent data analysis strategy. The researchers primary goal was to understand the entire scope of biologically inspired design to justify and further hone in on a credible researchable problem. Notes were used to organize thoughts and ideas that would inform the methodology in phase two and three.

Phase one identified clear terminology, the scope of the research problem, and identified integral researchers within the field. Meetings with biologists at The Biomimicry Institute, in which each three experts interviewed recognized the importance and confirmed the need for further development of a biologically inspired design toolkit with physical and visual artifacts. Seeing Dr. Yen's toolkit, at the CBID, was helpful to see how she used it to teach biologically inspired design (Figure 2). Meeting directly with Ph.D. student Michael Helms was integral to the understanding of problem versus solution-based approaches. Furthermore, conversations with Dr. Weissburg, Dr. Yen and Michael Helms were helpful in developing a tacit feel for the communicatory chasm this thesis intends to bridge. Interaction with these institutional leaders was pivotal in the early stages of research.

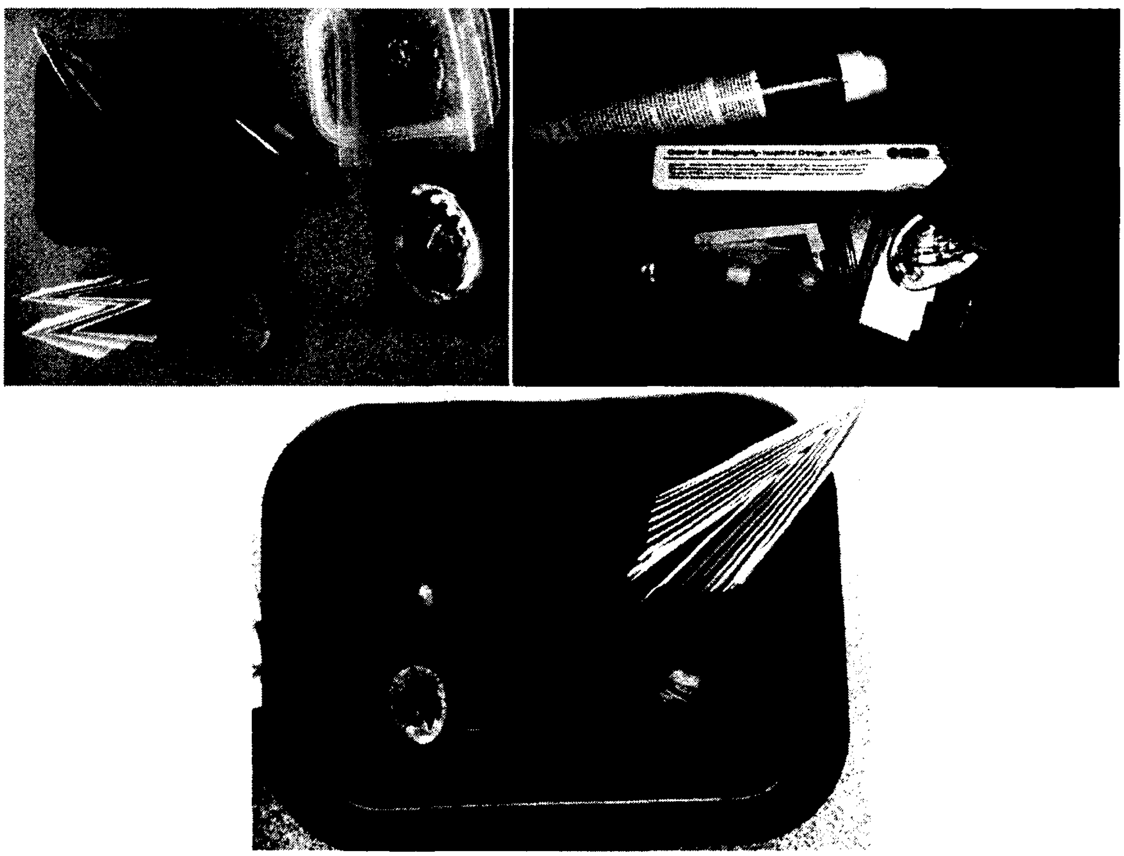

Figure 2. Dr. Yen's Toolkit

3.2 Phase 2: Interdisciplinary Design Discovery

This phase included the method of working with a biologist. This technique was applied subsequently to develop the toolkit described in Phase three. Collaborating with Dr. Jeffery Dawson from the Carleton Biology Department allowed the researcher to practice and evaluate some of the concepts covered in the literature review through discussion and observation. The interactions with Dr. Dawson were documented in a journal and with photographs. Working collaboratively with Dr. Dawson served three main objectives: 1) to practice domain information exchange to illuminate differences and similarities between biology and design methodology, language, and tools; 2) to extract relevant biological phenomena to apply to the design problems for use in a toolkit for furniture design; and 3) to help choose text, visuals, and objects or other relevant materials for use in a toolkit.

Approximately every two weeks the researcher met with Dr. Dawson for 1-2 hour discussions. These meetings lasted from January to April 2011. This took place at Carleton University's Biology Department. Meetings were held in Dr. Dawson's laboratory wherein the researcher was made familiar with insect samples, use of a microscope, and any other tools or biological examples that were beneficial. The researcher also attended a lecture given by Dr. Dawson, which covered insect sensory systems. See Figures 3 and 4 below for images of Dr. Dawson's class and microscope images gathered from the biology laboratory.

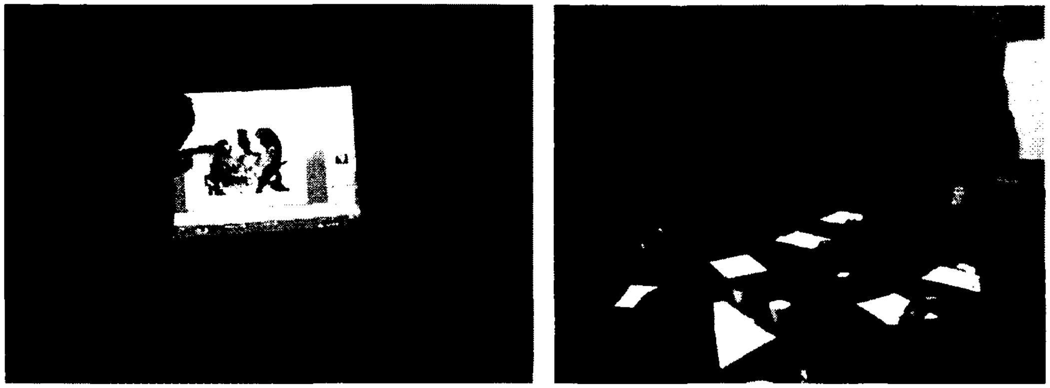

Figure 3. Lecture Images

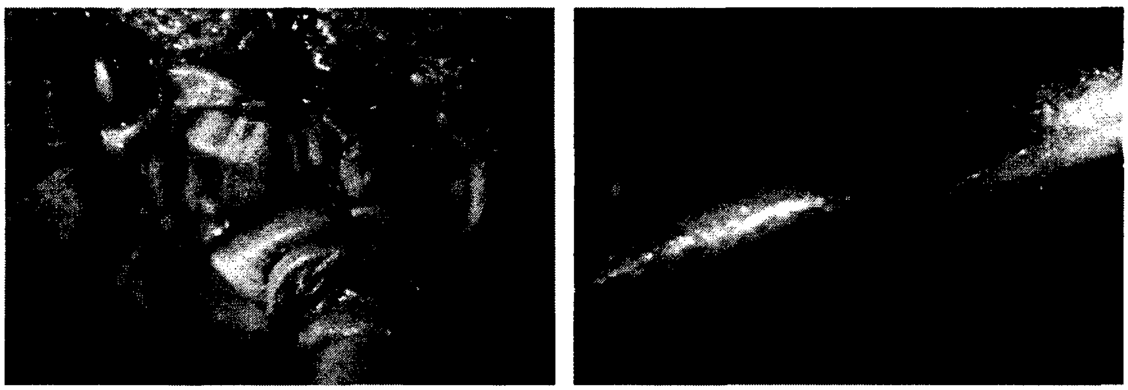

Figure 4. Microscope Images

Notes were transcribed into a narrative to summarize the researchers experience and learning. This was subsequently used as a reference for creating the toolkit and Phase three methods.

3.3. Phase 3: Testing the Toolkit

3.3.1 Creation of the Toolkit and its Environment

The idea of a toolkit arose from meetings with the champion institutions, observations from the literature and conversations with the researcher's supervisors. The development of the toolkit started in Phase two. The toolkit serves as a standalone and inspirational tool for designers. Designers interact with the toolkit to learn and experience nature's solutions. In between interviews with experts and discussions with supervisors it became evident that investigation into the benefits of tangible information was a researchable gap. Using pictures versus real artifacts became an important distinction that paved the way for two separate approaches, namely a two-dimensional and a three-dimensional toolkit. There were similar types of toolkits that were being utilized in the field but dissimilar to the toolkit that was developed for study in this thesis. The most notable difference is the inclusion of the specific furniture design examples. The idea was to show an analogy between human-made solutions and nature's solutions by organizing them into understandable principles. A lobster claw for example, is used to illustrate a natural way to achieve flexible strong joints by showing it next to a human-made furniture joint. This was intended to be a jumping point for designers to apply towards biologically inspired ideation: 1) to simplify the study by narrowing the focus; and 2) to evaluate the use of a toolkit within a defined problem area. Thus two types of physical artifacts (human-made versus biological) were both represented. In addition these had to be divided into 2D as well as 3D versions of the toolkit. Given the number and size of the objects, this was achieved by creating physical installations, described as a 2D environment and a 3D environment. See Figure 5 below for a topographical map of the environments (toolkits).

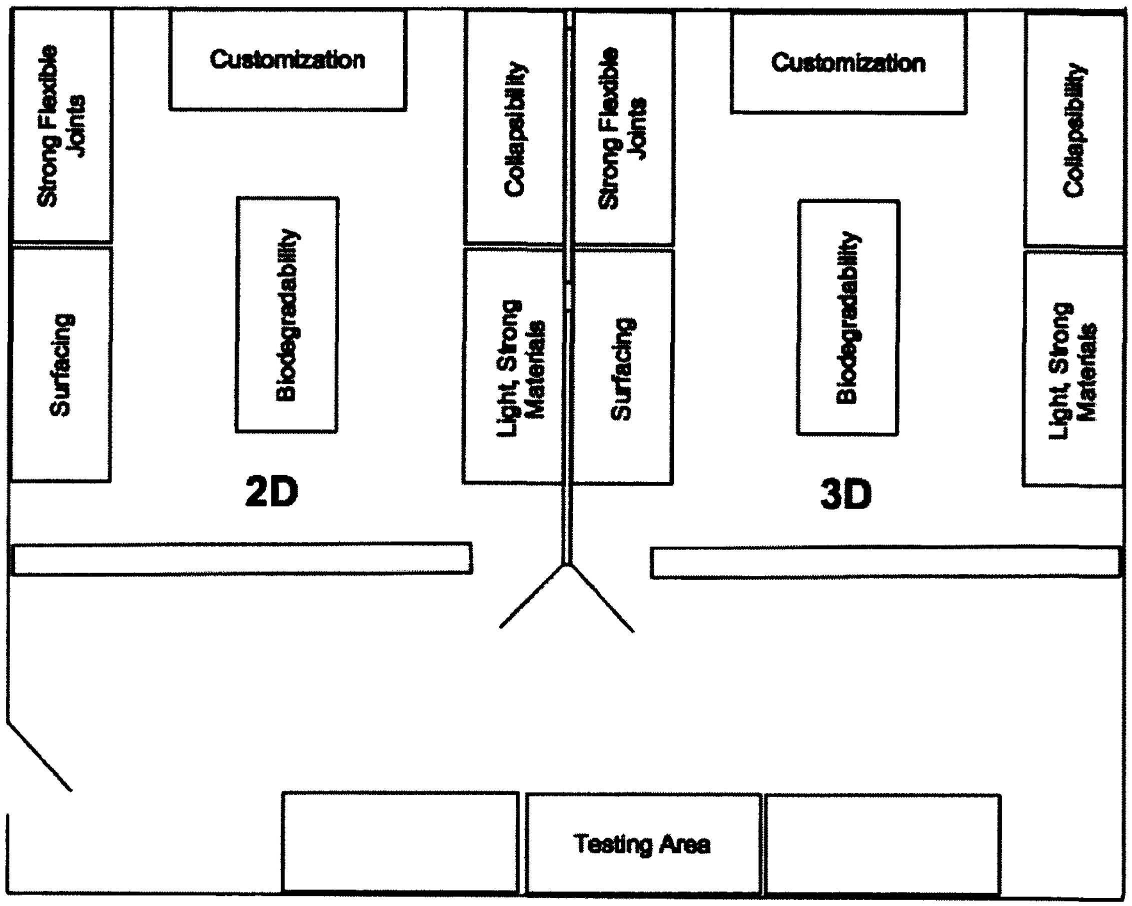

Figure 5. Topographical Representation 2D/3D Environments

It was decided that these artifacts would then represent six different compatible analogies between furniture design and biological examples. It was also decided that there would be six examples for each of the six analogies. See Table 2 below for the contents of the toolkit.

Table 2. Toolkit Contents

PRINCIPLE	FURNITURE DESIGN EXAMPLES	NATURES EXAMPLES
Strong Flexible Joinery	Rotating Joint Rotating Finger Joint IKEA Leg	Locust Leg Lobster Claw Chicken Leg
Biodegradability	Packaging Styrofoam Cardboard Box Plastic Tray	Mussel Shell Corn Fallen Leaves
Surface Treatments	Painted Metal Surface Anodized Aluminum PVC Fabric	Flesh Fly Lotus Leaf Butterfly
Collapsibility	IKEA Table Folding Table Collapsing Table	Pines Cones Palm Frond leaf Beetles Wings
Light Strong Structures	Lightweight Panels Steel Tubing Moulded Plastic Chairs	Scallop Bamboo Palm Frond Stem
Customization	Size Colour Form	Herbivore Jaw Bone Ivy Wasp Nest

See Figure 6 a) and b) below to see a basic layout of the environments and the toolkits that reside within them.

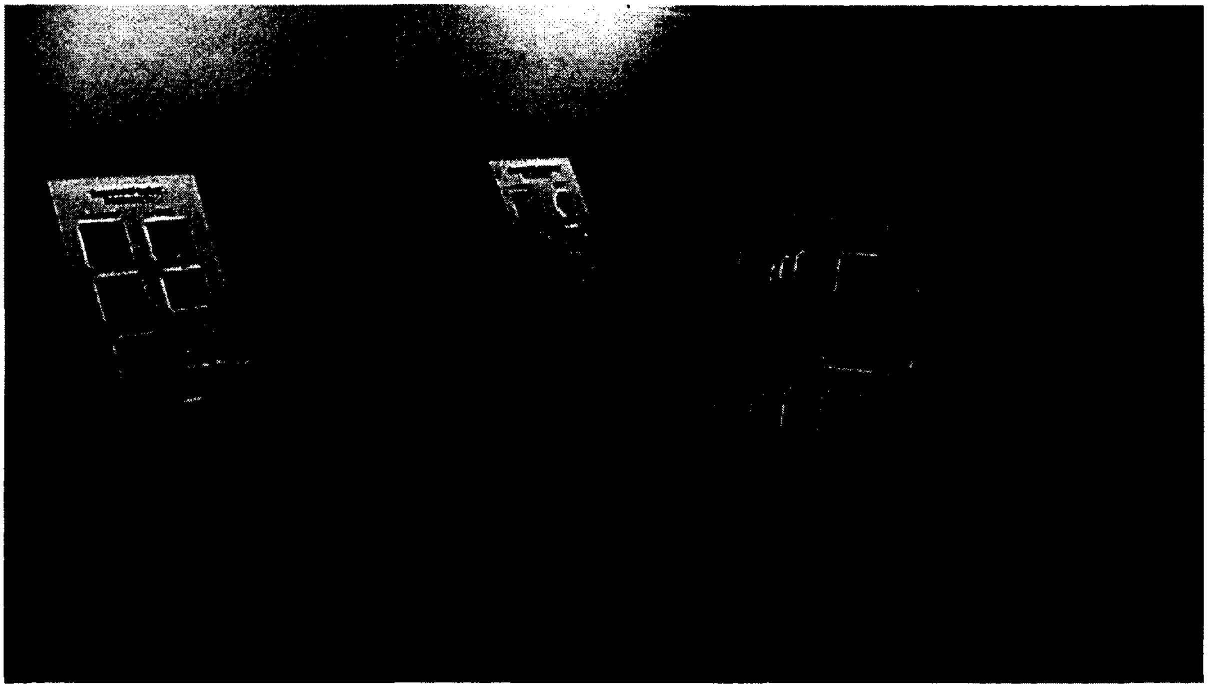

Figure 6a. 2D Environment (Toolkit)

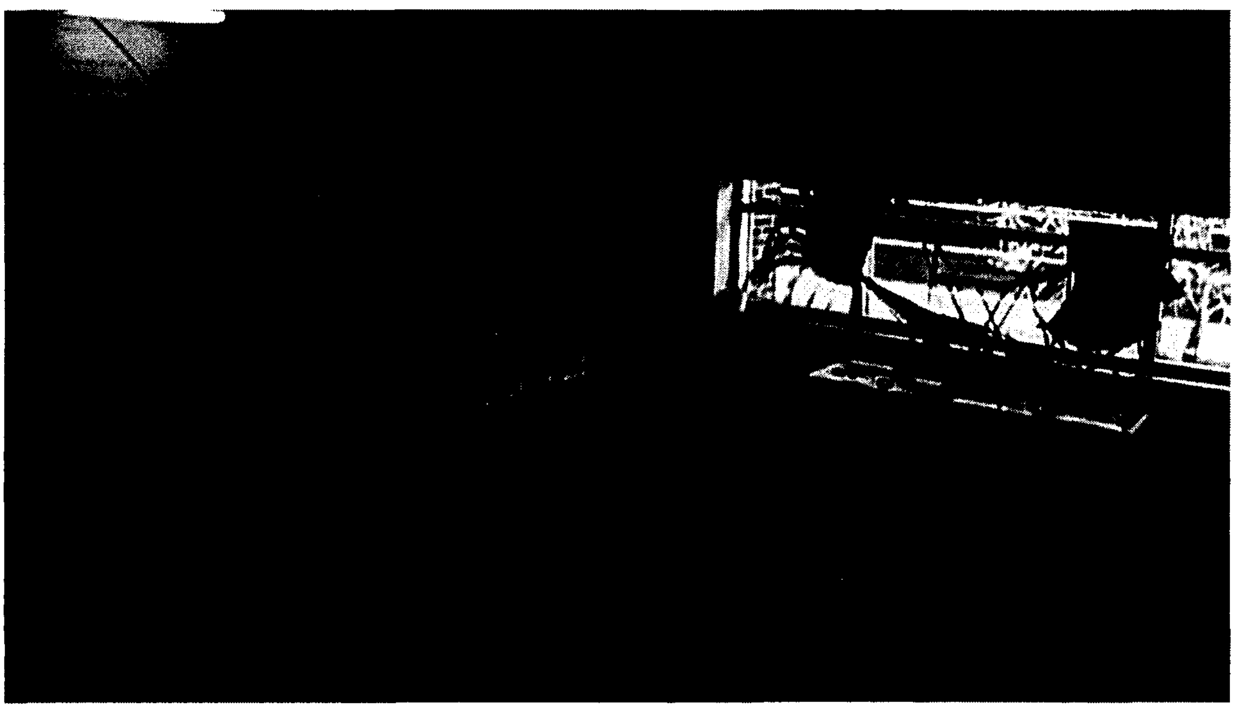

Figure 6b. 3D Environment (Toolkit)

3.3.2 Qualitative and Quantitative Methods and Data Analysis

Text was seen to play a vital role as part of the stimuli. Text was displayed with the same font and size for the 2D and 3D environments. All fonts were Arial and black and all backgrounds were white. The 2D visuals were scaled as close as possible to the size of their 3D counterparts. The different environments were also setup in the same orientation to further limit any variation. One student at a time could then interact with the stimuli at each station before being given the design challenge and retention test. The detailed content of the toolkits can be viewed in Appendices D and E.

Increasing validity of the methods was an upmost concern of the researcher. Consulting with the EDC was an integral step towards this. This is also true for the consideration taken when designing the two different environments as mentioned above. Other considerations were made such as the request for participants not to communicate with other participants outside of the workshop and conducting a pilot session with other graduate students to identify any issues that may arise.

Direct communication with a biologist was used to select information for use within the biologically inspired design method and a mixture of problem-based and solution-based approaches were utilized within the structure of the methods. These are two of the primary variables in relation to a biologically inspired design method covered in the literature review that remained static. The intention was to find an approach that would allow the researcher to study biologically inspired design information representation.

Phase three used a mix of qualitative and quantitative data collection through administration of a retention test, an experiential survey, and a design challenge. A pilot session was first conducted with graduate industrial design students as the participants. It was treated more as an informal user testing session than a formal experiment. A mix of graduate design and senior design students were ushered through the itinerary and given a synopsis of what the actual participants would be doing. The goal was to garner feedback from knowledgeable designers on the quality of the procedure, the toolkit and their corresponding environments. What follows is an account of the procedure applied in reaction to Phases one and two of the research methods and this pilot session.

Select undergraduate industrial design students participated in a 1.5 hour-long session that took place at the MDes studio in the Azraeli Pavilion during the week of April 11-15, 2011. The studio is approximately 20'x20' in dimension. Two separate environments were created using room dividers. Each environment was approximately 10'x7' in dimension. Six tables that represented 6 different analogical examples were set up in each environment. The study involved a convenience sample of 23 students. However their assignment within the study is purposeful in respects to year of study and GPA. No distinction was made between participants in respect to sex. There were representatives from all four years of undergraduate program. There were 2 from first year, 6 from second year, 17 from third year, and 9 from fourth year. Seven of the students originally signed-up withdrew.

Upon entry to the graduate studio students were given a random number if which the researchers were unaware. They would use this number to sign all documents within the study. This number and the respective names were sealed in an envelope for blind data analysis. Following this procedure and consent form completion, an independent questionnaire was distributed to establish whether or not there were any outstanding students with significant experience or knowledge in biology. This would help with the accuracy of the findings further down the road; Appendix F displays this independent survey.

Following the identification procedure the participants were greeted and given an introduction that explained the research and the purpose for their involvement. The entire itinerary can be viewed in Appendix E. Following this introduction, testing commenced. A pre-survey was administered (Appendix F). Because researchers were evaluating not just the effectiveness of the toolkit on a whole, but also the effectiveness of 2D artifacts versus 3D artifacts, it was important that the participants were divided into two groups. One group would experience and be tested on the 2D experience and the other would be tested on the 3D experience. Each group would be represented as best as possible with equal members from the same year of study and similar academic abilities. This was important to evaluate the effect that the different toolkits had on the participants in terms of information retention. The 2D toolkit would be compared to the 3D toolkit. Each contained the same information but in different mediums. The 3D environment contained physical objects from nature and furniture design that the participants were encouraged to interact with. The 2D environment had exact image representations of those physical models. Twelve participants only, experienced the 2D environment and the other 12 students experienced only the 3D environment. Using an identical survey (Appendix F) to be administered before and after each 12-minute experience, quantitative data could be analyzed to measure any differences between the two groups. There were six stations in which each participant in a bell-testing fashion would be encouraged to interact, learn, and be inspired. Three or four students entered the environment at a time. When one environment was open the other environment was closed. One workshop consisted of two groups. One group was exposed to the 2D environment and the other was exposed to the 3D environment.

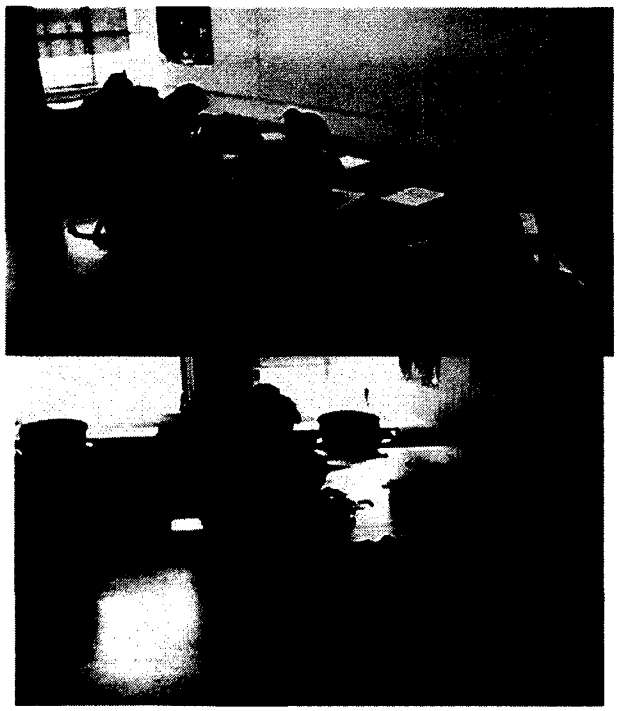

Figure 7. Testing the Participants

As mentioned, after exiting the environment both groups were given the post-test identical to the pretest. This provided quantitative data to evaluate differences in efficacy, if any, between the two environments, in respect to knowledge retention. Once complete the participants were given a design challenge in which they were asked to sketch ideas for a table design that would incorporate innovative biological principles. This challenge was altered from one day of testing to the next. See Appendix G for the altered design challenge. The only difference from the original is that the participants are asked to reenter the environment. The results of this alteration will also be discussed in Chapter four. Originally, data collection and analysis intentions had the researcher looking to evaluate the quantity of ideas that would emerge from this exercise. Comparisons were made between design challenge outcomes from the 2D group and the outcomes from the 3D group. This remained constant. The sketches, from the design challenge were analyzed by the researcher and advisors, to evaluate their originality and the toolkits overall affect on inspiration.

Possibly the most important measure was administered following the design challenge. It was the experiential survey that would collect qualitative and quantitative data in respects to the participants' reactions to the use of a toolkit. This survey (Appendix F) would prove invaluable to evaluating the primary thesis question: Does a stand-alone installation of biological information inspire designers?

Before leaving the participants were thanked and asked, in trust, not to discuss their experience in any capacity with other SID undergraduate students. This would help control contamination of the results.

A triangulation strategy was used to evaluate the affect of the toolkit on the researchable questions. This includes application of the pre/post retention test, the design challenge, and the experience survey wherein qualitative and quantitative data could be collected and analyzed. See Figure 8 below for an illustrative model of the applied strategy.

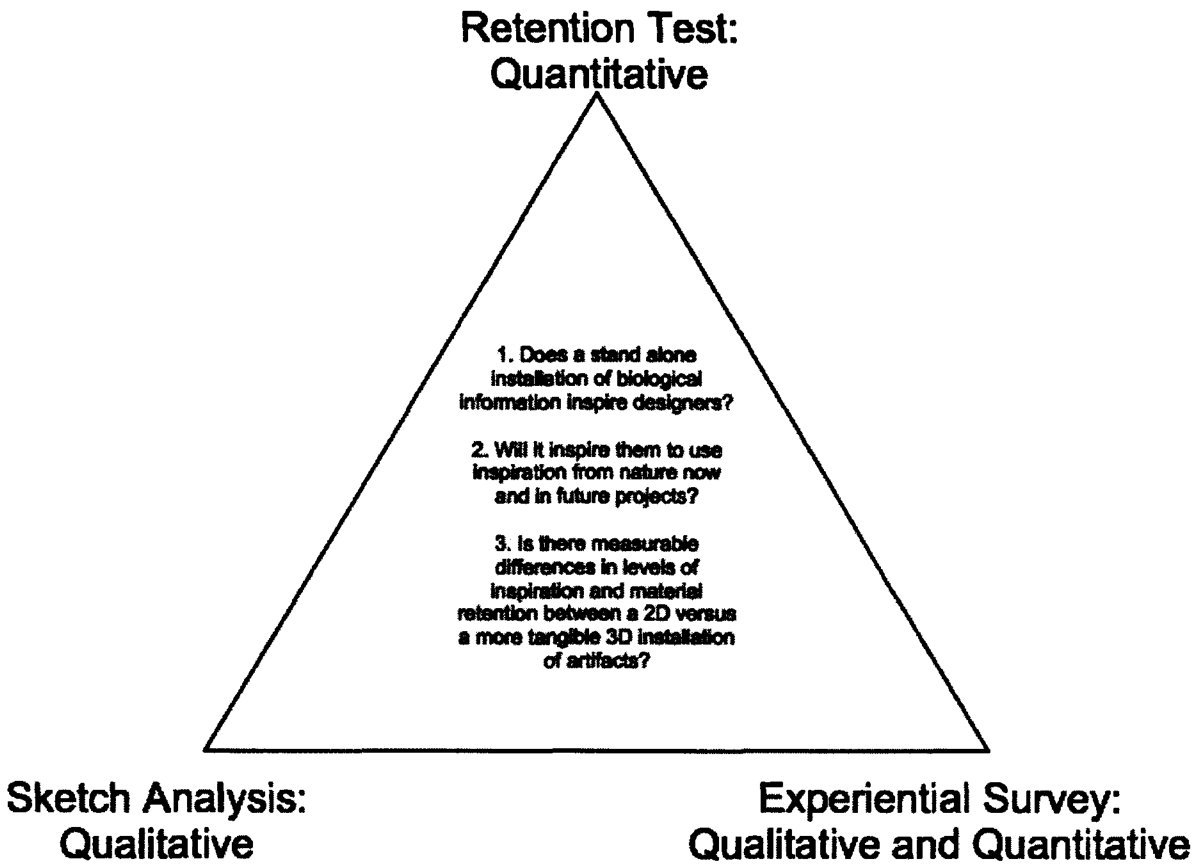

Figure 8. Triangulation Strategy

Descriptive statistics from the retention test and the first three questions in the experience survey were entered into a spreadsheet for analysis. Scores from the retention tests were tabulated and entered into these spreadsheets. The statistics could then be rearranged for comparison and analysis. The mean scores from each workshop could then be compared and evaluated to its counterpart. The mean scores of the 3D and 2D workshops were also compared to evaluate which set of workshops fostered more knowledge retention.

The qualitative data was also entered into a spreadsheet. Relevant responses were tabulated and color-coded into noticeable trends. These trends were placed into seven categories. There were 74 categorized relevant responses. Each different category, depending on its number of responses, could then be assigned a percentage of the total. Reviewing the students' table sketches was a much simpler process of analysis. The researcher was looking for evidence of novel idea generation. The sketches were analyzed blindly to highlight any examples that presented this quality. They were also looked upon for evidence of practicality and use of biological concepts in the designs. Relevant findings are discussed further in the following chapter.

CHAPTER 4

RESULTS & DISCUSSION

Three problem areas were identified that could be explored to help in development of such a methodology. These were: biological information transfer; biologically inspired design methodological structure; and biologically inspired design information representation. The first two phases of this study were emergent and necessary for development of the methods used in phase three. Phase three was the testing of the resulting toolkit informed from phase 1 and 2. A triangulation strategy was used to explore the following questions:

1. Does a stand-alone installation of biological information inspire designers?

2. Will it inspire them to use inspiration from nature now and in future projects?

3. Is there measurable difference in the level of inspiration and material retention between a 2D versus a more tangible 3D installation of artifacts?

Before the surveys were given all participants were screened in this study. The independent questionnaire (Appendix F) administered made it clear that there were not any participants who had exceptional biology knowledge or experience that would skew the results.

4.1 Retention Test

There was a significant increase in retention scores (pre score test compared with post score test) in both the 3D and 2D artifact groups. In the 3D group (Figure 9, blue bars) test scores increased from 55.3% to 76.9% (a difference of 21.6%) (Paired t-test (one-tail), t=-3.75, n=9, P=0.0028) and similarly, in the 2D group (Figure 10, green bars) test scores increased significantly from 59.2 % to 73.8% (a difference of 14.6%) (Paired t-test (one-tail), t=-5.04, n=9, P=0.0002).

These results indicate that students learned something in both 3D and 2D groups. However it was hypothesized that the 3D toolkit would have a greater 'benefit' to the students and thus that it would be reflected in better retention scores. Further analysis of the results showed that students exposed to the 3D toolkit did not retain more (i.e. score a greater difference (post-pre) on the retention test) than students exposed to the 2D toolkit. Thus, although numerically the 21.6% increase seen in the 3D group is greater than the 14.6% increase seen in the 2D group, statistically speaking, there is actually no difference. This is most likely because there were more students in the 2D group than in the 3D group. (t-test (one tail), t=1.167, N=9,12, P=0.129).

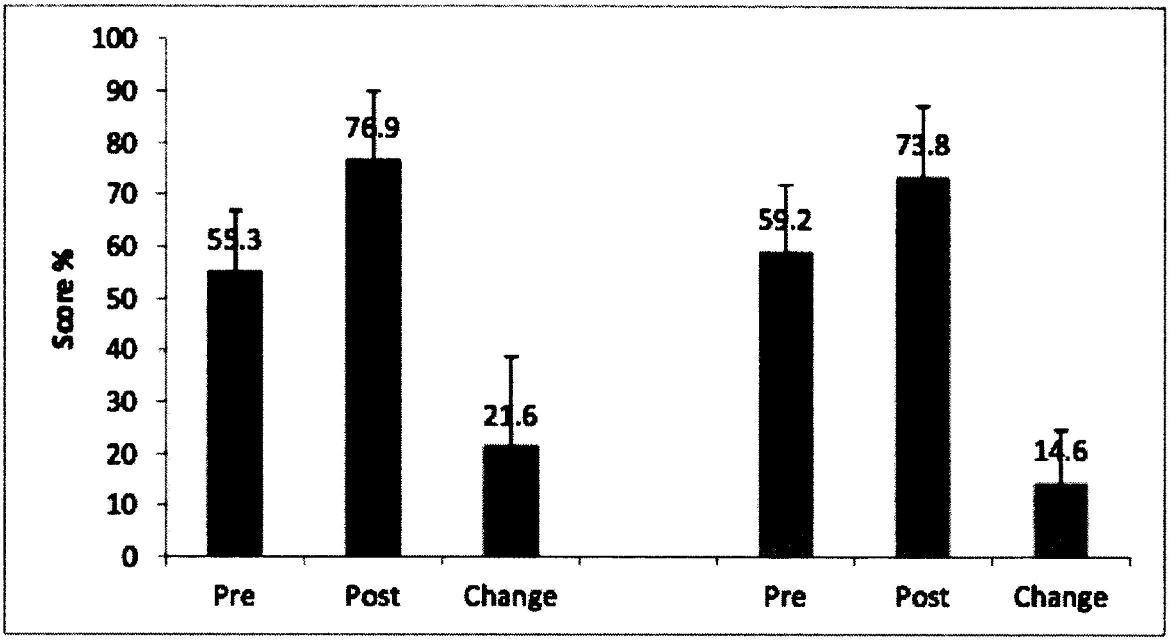

Figure 9. Retention test scores. Blue bars are data from the 3D group, green are data from the 2D group; values above the bars are means and whiskers are standard deviation. Change is simply the difference in pre and post scores (post-pre) calculated per student then averaged.

There is one notable statistic, which is the minimum score of a pre-test in the 3D group. A participant scored 1% on the pre-test. It was later found that the participant's score was reflective of an English language barrier. This score was removed to provide more accurate statistics.

Participants did show a tendency to retain knowledge after experiencing the either one of the toolkits. It was also clear that the participants in the 3D environment showed a trend towards better knowledge retention. It would seem that visuals and objects both play important roles in the development of the biologically inspired toolkit.

4.2 Experience Survey: Quantitative and Qualitative

The experience survey was administered to record feedback from participants about whether they learned something, were inspired, and if they would use a biologically inspired design approach again in the future. This was administered at the very end of the workshop and thus gathered participant feedback about experiencing the toolkit, being tested, and taking part in the design challenge. Refer to Appendix F to view the experience survey that was administered. The first question was administered with the purpose of gauging an overall reaction in the context of inspiration received from the toolkit. The 3D group rated this question significantly higher than the 2D group. (t-test (one-tailed), $t=2.032$, $N=10, 12$, $P=0.028$). This means that the 3D group felt more inspired. The next question asked was whether or not the student felt they learned something about biology. The 3D group rated this question significantly higher than the 2D group. (t-test (one-tailed), $t=1.817$, $N=10, 12$, $P=0.042$). The last question asked whether or not the participant learned anything about design. The 3D group rated this question neither higher nor lower than the 2D group. (t-test (one-tailed), $t=1.003$, $N=10, 12$, $P=0.164$).

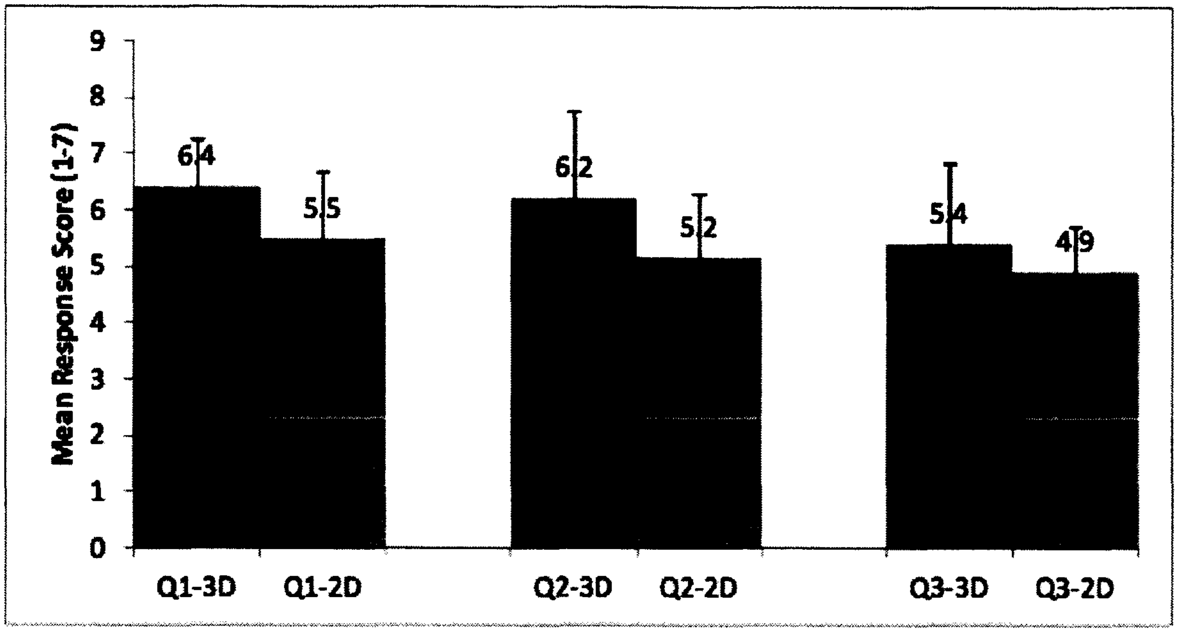

Figure 10: Average response scores from the experience survey questions 1-3. Responses from students in the 3D group are in blue, responses from students in the 2D group are in green. Values are averages, whiskers are standard deviation. N=10 for the 3D group, N=12 for the 2D group.

The qualitative data collected was divided into two major themes and six sub-categorical themes. The two main themes that emerged were positive feedback versus negative feedback. The feedback was overwhelmingly positive in which (96%) of the questions asked rendered positive remarks. The six sub-themes that emerged, two of which were categorized as examples of negative feedback and the other four as positive feedback were as such: Positive Feedback 1) described helpful interaction; 2) described helpful visualization; 3) described helpful for inspiration; 4) described that they will use biology in the future; Negative Feedback 1) described ambivalence about using biology in the future; 2) requested more or different information. A seventh category concerns the change in protocol discussed in the final section of this chapter.

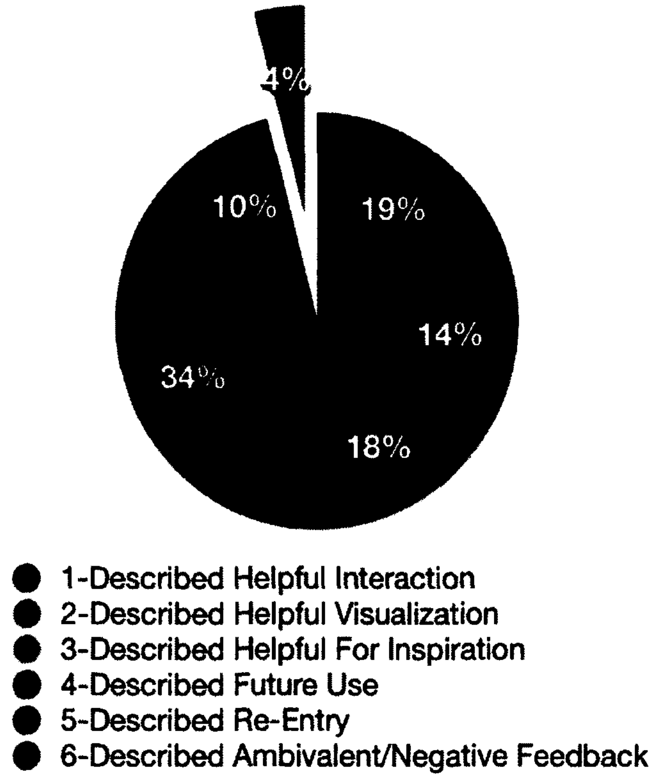

Figure 11.Categorized Comments from the Experience Survey

Data organized under the previously mentioned categories affect each one of the three research questions of this thesis. For example under category 1, 'described helpful interaction,' it seems that participants reacted very positively to interaction with the objects. One participant who experienced the 3D toolkit replied, "Tactile interaction helped me plan my design better." Another participant stated, "...being able to see and touch artifacts benefitted my understanding and link ideas." This feedback coincided with the descriptive data finding of this survey also. It was clear that participants were excited about interacting with the physical objects. A third participant mentioned, "textures, scale and the mobility of the different artifacts were extremely helpful."_ However, participants in the 2D workshop also reported positive feedback. Not so much under the category of interaction but under category 2, 'described helpful visualization.' One participant reported, "Structural concepts were extrapolated from the natural/bio pictures." Another participant of the 2D workshop stated, "If there were no images I may have not been so inspired." Participants within the 3D workshop also reported positive affects on visualization. One student reports, "Visualization helped through interaction and engagement." Participants in the 2D and 3D workshops were both reporting positive feedback from interaction with visuals and objects. Other feedback directly affected the third category of emerging trends, 'described helpful for inspiration.' A participant suggests that they were looking "at joints in detail, for inspiration." Another was quite detailed in their account, "I will use biology to increase my focus on sustainability and to inspire ideas on functionality." An interesting comment from one participant was, "If I can't come up with something, I'll look to nature for more inspiration." These examples reinforce the descriptive data that emerged from the first question of this survey, Appendix F. Furthermore, the qualitative data collected directly relate to this thesis's researchable questions. Participants were readily willing to suggest they would use biology as a source for inspiration in the future. One participant states, "I will certainly research more into biological solutions to my design problems in the future." Another states, "...there are many ideas to be explored, they can be translated into design processes that are cost effective and environmentally friendly." One interesting quote goes as such, I will use biology in the future "when possible and feasible."

Not all feedback was positive. There was a small sample of participants who were either ambivalent or responded negatively about using biology in their design process in the future or about being inspired. One participant stated, "...it was not so clear how the process of drawing inspiration from nature could happen." Another participant, when asked whether they planned to use biology in the future, answered, "Yes, but there are a lot of higher things on my list." When a participant in workshop five answered a question about re-entry to the environment after the challenge was given they stated, "entering the second time loses the 'wow' or inspiration factor." Though altering the intervention to allow re-entry had mostly positive feedback from the participants. This was significant because it made the design challenge more of a problem-based approach. When asked if it helped to re-enter the exhibit a participant answered, "Yes, when presented with a design brief, you look for certain information that could help you." Another responded with, " Yes. I forgot some details and wanted some more opportunities to inspect the items under a new light. Having a specific task changed what I was looking for."

Based on the surveys it was convincing that industrial designers felt they would benefit from a toolkit. The feedback suggests such a tool would be quite welcomed and would have beneficial affects on inspiration levels.

4.3 Sketch Analysis

It is clear from the data analysis of the experience survey and the retention test that there is a positive affect on the participants from both environments. The design challenge also rendered interesting results that coincide with these previous findings. Please refer to Appendix G for another look at the design challenge. The participants' innovative ideas also coincided with positive feedback from their experience survey. Participant 272 stated, "Being able to physically interact with them was important, as well as comparing them to other examples." Whereas the sketches were reviewed subjectively, the objective was simply to look at evidence of biological inspiration. Was there evidence that biological information had been incorporated as a manufactured furniture analogy? This evidence would further help in the triangulation of results to see if students would be positively inspired.

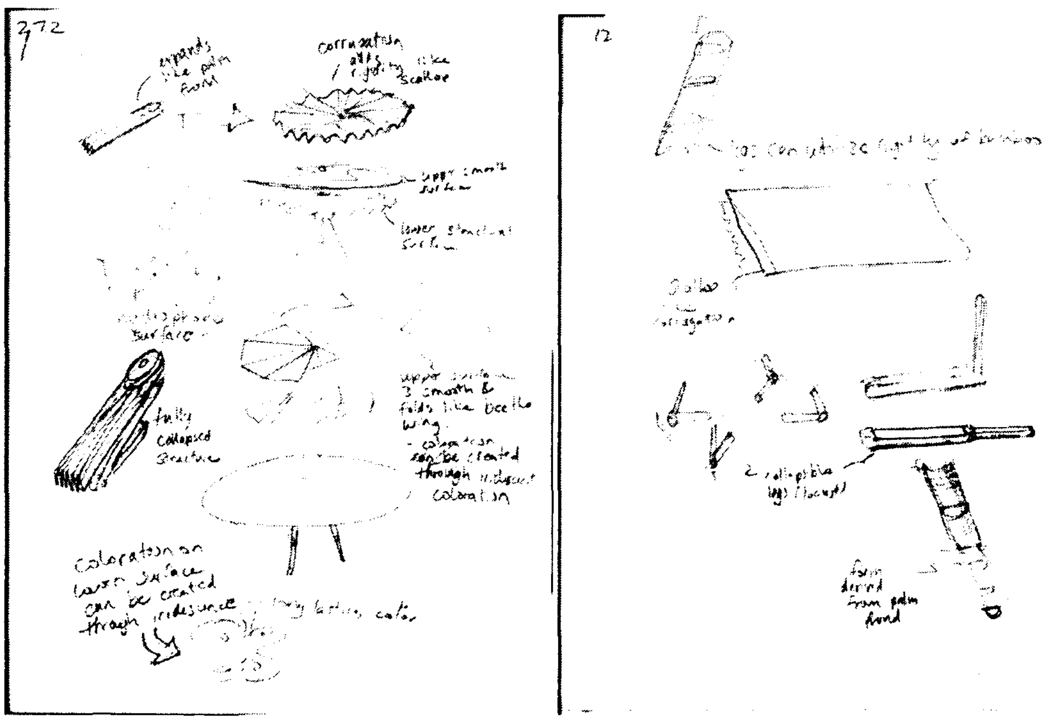

Figure 12. Participant 272 Sketches

The concept by participant 272 for example clearly exemplifies solutions that deal with design problems such as surface wear, collapsibility for shipping and ease of use, normal functioning, and beauty. The translations of biological phenomena to design mechanism are very literal in this case. Doing so the participant developed a short-distance analogy as described by Chui and Shu (2002). This is a good example of how the toolkit should work ideally for this level of information.

Participant 172's, who also experienced the 3D toolkit, comment also correlates positively with their sketch concepts. When asked how the artifacts help to visual design ideas, the participant states, "using the way they moved and translating it into the way a furniture could move." This participants sketch can be viewed below.

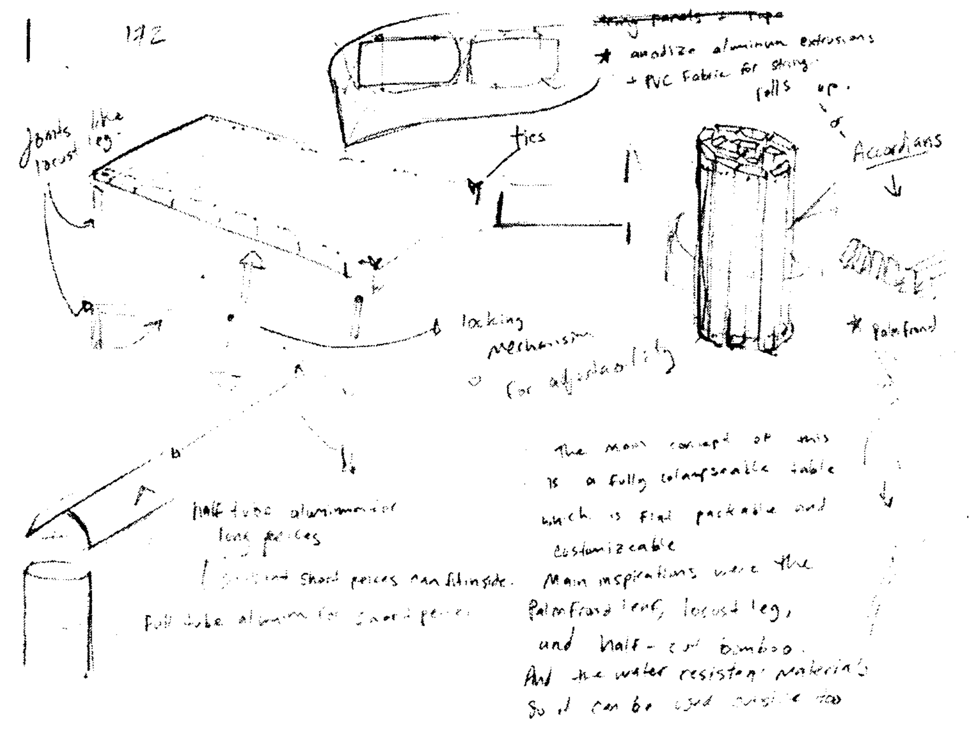

Figure 13. Participant 172 3D Sketch (A)

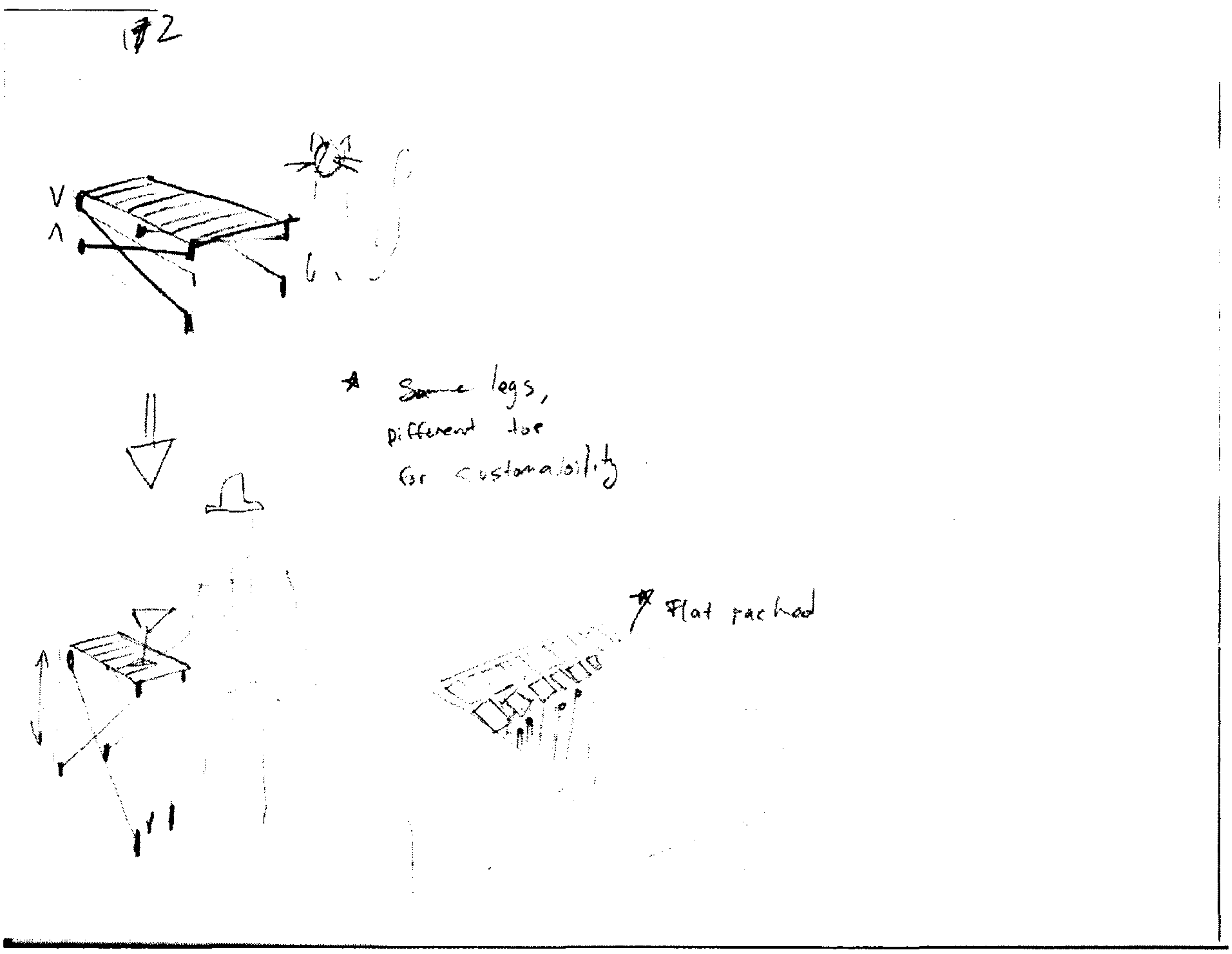

Figure 14. Participant 172 3D Sketch (B)

The following are two selected sketch concepts from participants. Participant 613 shows a clear problem based approach and uses the challenge of collapsibility by using nature's analogies. Participant 807 however displays the typical designer's ability to 'drift'. The solution for a table that drains the water did not exist in the design challenge, but has been introduced as a solution driven design problem.

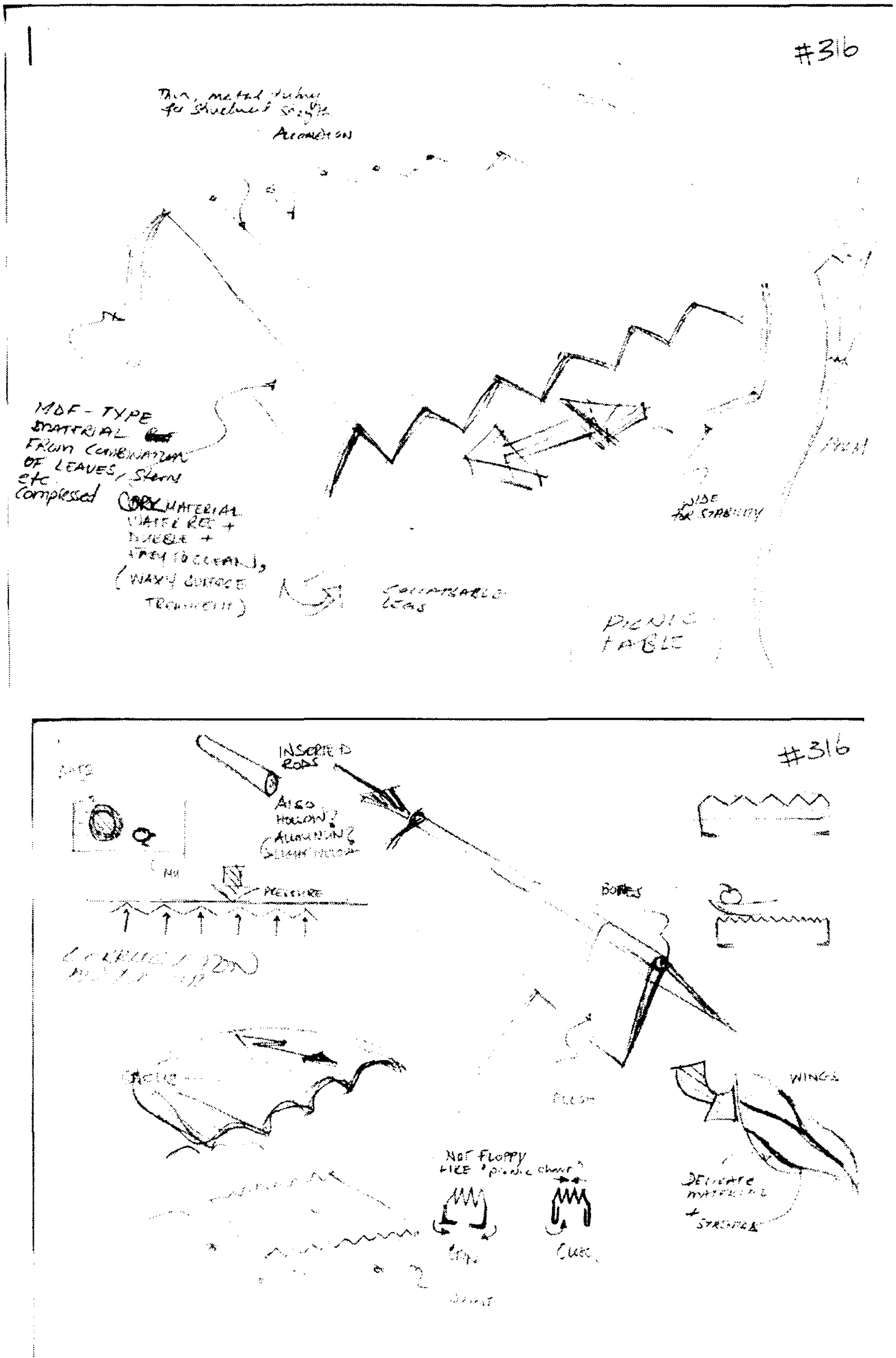

Figure 15. Participant 613 3D Sketch (A) & (B)

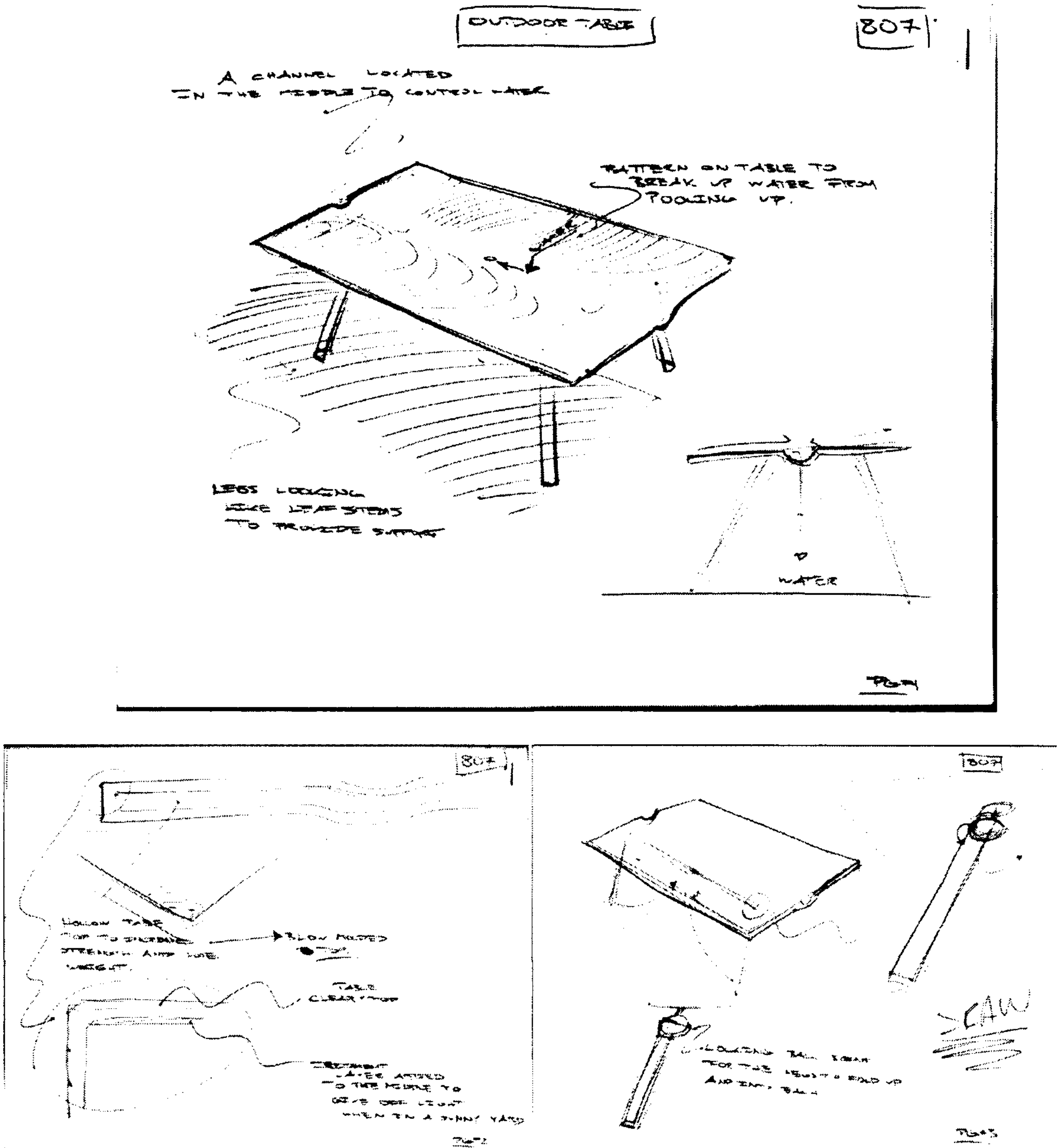

Figure 16. Participant 807 2D Sketch (A), (B) & (C)

4.4 Discussion of a Problem-Based *versus* a Solution-Based Approach

As noted in the methods above participants in workshops four, five and six were required to reenter the environments. This change in protocol and the resulting feedback leads researchers to believe that a problem-based approach is necessary for inspiration. Re-entry into the environment allowed participants to search for solutions with a specific task at hand. They were able to mine for relevant information that inspired their ideation process. It also reasserts Cross's (2004) concept of 'drifting'. Allowing designers to move back and forth and back again, among mediums, sparks creativity. To reiterate, participant 499 when asked whether it was helpful to re-enter the environment answered, "Yes, I got to really consider the implications of each fact on the design and its context." Another participant stated, "Having a specific task changed what I was looking for." The specifics of the task is something the researchers believe should be further explored. This design challenge was broad to allow for flexibility inside structured protocol. Results from this thesis suggest that the specifics of this task lead to beneficial outcomes. One other participant answered the same question with a less positive response, "Re-entering helped to reinforce material, but second time loses the 'wow' or inspiration factor." On the whole, it seems re-entering the environment once a task was given was well accepted by the participants.

The answer to our first researchable question is that students reacted very positively to a stand-alone toolkit. All three methods applied within the research design point towards this effect. Statistics show that on average the participants rated experience of both environments at 5.9/7 and the qualitative feedback was overwhelming positive with only 4%

of all response being ambivalent or negative with comments about the toolkit. The retention test shows there is significant learning occurring when experiencing both toolkits. Though not surprising, it is the matching of creative output exemplified by the sketch outputs that makes the primary researcher very hopeful for future development of a toolkit for biologically inspired design.

The feedback for researchable question 2 was also very positive. Of 74 categorized responses, 34% described using biology in the future. Of the three researchable questions, it is the third that has inconclusive results. It is unclear whether a 3D or 2D toolkit has a greater affect on knowledge retention. Though as mentioned both have positive affects. In terms of inspiration, there is trend in the qualitative data that suggests participants gained more inspiration from the 3D toolkit opposed to the 2D toolkit. This trend and the inconclusive findings about the difference in efficacy as measured by knowledge retention are in need of further exploration. This and other suggestions for further research will be discussed more in the following chapter.

CHAPTER 5

CONCLUSIONS & SUGGESTIONS FOR FUTURE RESEARCH

This study concludes that toolkit described herein serves to inspire design students to produce novel furniture designs. There was a clear trend that suggested a 3D toolkit has benefits over a 2D toolkit for knowledge retention, furthermore the data showed that it was more inspirational than the 2D toolkit. Participants who experienced the 3D toolkit gave feedback that suggested they would rather interact with physical objects than pictorial representations of objects, when generating ideas for biologically inspired designs. A multimodal presentation of the toolkit including text, visuals, and physical objects is thus most beneficial to knowledge retention and inspiration.

The protocol selected within this study was based on data collected from the first two phases and was used to create a biologically inspired method. As a change in this thesis's protocol half way through the study revealed a problem-based approach was desirable, the researcher suggests creating and studying the effects of a more problem-based toolkit would be beneficial. That is, the participants would not be exposed to the solutions at all until they are exposed to a more refined design problem. The researcher feels this would spawn very interesting results in terms of inspiration and quality and quantity of concept generation. Other changes that would yield interesting and differing results would be as such: altering the amount of textual information for quantity and complexity; experimenting with short and long-distance analogies; and experimenting with different information presentation mixes.

Given the fact that the design community is putting a lot of emphasis on biologically inspired design solutions and the fact that a toolkit can be used effectively to accomplish this, more work could be done to make such a toolkit more practical. The current toolkit is in effect an installation and as such it takes up considerable space and has not been designed to be mobile. Furthermore, the problem with biological artifacts is that they are finite in their lifespan (decomposable). Solving these problems is therefore a worthwhile research exercise.

This research demonstrates the benefits of a biologically inspired toolkit. The researcher suggests further research on this topic in more detail would be beneficial to the field.

5.1 Research Limitations

As this field is very large in scope it was necessary to attain some focus by making two decisions. Firstly, only industrial design students participated in this study. Secondly, the toolkit principles were applied to furniture design. Utilizing alternative participants from other fields or artifacts the results would be expected to be the same within reason.

BIBLIOGRAPHY

Benami, O, Jin, Y., (2002). Creative Stimulation In Conceptual Design. *Proceedings of ASME DETC/CIE*, Montreal, QC, Canada, DETC2002/DTM-34023

Benyus, J. M. (1997). *Biomimicry.* New York: HarperCollins Publishers Inc.

Biomimicry Institute, T. (2007-2009). Retrieved October 7th, 2010. http://www.biomimicryinstitute.org/case_studies.php

Bonser, R. (2006). *Patented Biologically-inspired Technological Innovations: A Twenty Year View.* Journal of Bionic Engineering, 3, 39-41.

Bonser, R. & Vincent, J. (2007). *Technology Trajectories, Innovation, and the Growth of Biomimetics.* Mechanical Engineering Science, Vol. 221, 1179-1180.

CBID. (2010). *The Center for Biologically Inspired Design.* Retrieved October 20th, 2010. http://www.cbid.gatech.edu//

Chiu, I., Shu, L. (2004). Natural Language Analysis for Biomimetic Design, Proceedings of ASME DETC/CIE, Salt Lake City, UT, DETC2004/DTM57250.

Cross, N. (2006). *Designerly ways of knowing*. London: Springer.

Edwards, J. (1997). Crude Oil and Alternate Energy Production Forecasts for the Twenty-First Century: The End of the Hydrocarbon Era. AAPG Bulletin, 81(8), 1292-1305.

Forbes, P. (2005). *The Gecko's Foot.* London: Harper Perennial.

Gebeshuber, I. C., Gruber, P., & Drack, M. (2009). A gaze into the crystal ball: Biomimetics in the year 2059. *Proceedings of the Institution of Mechanical Engineers.Part C, Journal of Mechanical Engineering Science, 223*(C12), 2899-2918.

Goldschmidt & Sever. (2009). From Text to Design Solution: Inspiring Design Ideas With Texts. *Proceedings of the 17th International Conference on Engineering Design.* Vol. 9, 15-26.

Helms, M., Vattam, S. S., & Goel, A. K. (2009). Biologically Inspired Design: Process and products. *Design Studies, 30*(5), 606-622.

McDonough, W. & Braungart, M. (2002). *Cradle to Cradle.* New York: North Point Press.

Rhoten, D., & Parker, A. (2004). Risks and Rewards of an Interdisciplinary Research *Path Science, 306*(5704), 2046-2046.

Shu, L. H., Ueda, K., Chiu, I., & Cheong, H. (2011). Biologically inspired design. *CIRP Annals - Manufacturing Technology, 60*(2), 673-693.

VINCENT, J. F. V., BOGATYREVA, O. A., BOGATYREV, N. R., BOWYER, A. & PAHL, A.-K. (2006). Biomimetics - its practice and theory. *Journal of the Royal Society Interface*, April 2006.

Vincent, J. & Mann, D. (2002). *Systematic Technology Transfer From Biology to Engineering.* The Royal Society, 360, 159-173.

Vogel, S. (998). *Cat's Paws and Catapults.* New York: W.W. Norton & Company.

Volstad, N. L., & Boks, C. (2008). In Roosimolder L. (Ed.), *Biomimicry - a useful tool for the industrial designer? shedding light on nature as a source of inspiration in industrial design.* TALLINN; DEPT MACHINERY, EHITAJATE TEE 5, TALLINN, 19086, ESTONIA: TALLINN UNIV TECH.

GLOSSARY

Analogical Representations: Relevant biological information that serve as effective analogies for specific design problems
Biologically Inspired Design: Taking inspiration from nature to apply to human design problems.
Biologically Inspired Toolkit: A collection of objects, visuals, and texts that represent relevant biological and design information.
Effects: Related to performance principles such as knowledge retention and inspiration.
Environment: 2D or 3D, the room in which one of the toolkits exists.
Natural Language: Wherein the verb-object and agent-verb relationships follow from English-language grammar rules. It is a field of linguistics and computer science that fosters the relationship between humans and computers.
Toolkit: A collection of interactive 2D graphics, 3D models, and text that aid in the conveyance of a certain topic.

APPENDIX A

CASE STUDIES

Velcro
Bio-Inspired Product Design
Product

Carleton University
Masters in Interdisciplinary Design
IDES 5201
Lorenzo Imbesi
Peter Wehrspann

Project Details

Inventor: George De Mestral
Company: Velcro Corporation
Keywords: Bio-inspiration, Nano-technology, microfabrications, natural solutions
Date: 1955-Present
Website:www.velcro.com/

Velcro is a brand name of fabric hook-and-loop fasteners.It consists of two layers: a "hook" side, which is a piece of fabric covered with tiny hooks, and a "loop" side, which is covered with even smaller and "hairier" loops. When the two sides are pressed together, the hooks catch in the loops and hold the pieces together. When the layers are separated, the strips make a characteristic "ripping" sound.

Innovation

It must be noted how this invention and creation of bio-inspiration came to be a ubiquitous product in modern culture. As it was definitely biological inspiration at its best, it was an unintentional discovery. This can be the nature of innovation at times and understanding Velcro's story is integral to refining innovative methods for the purpose of biologically inspired design.

It is said George De Mestral was frustrated with fastening his wife's dress before going out for the evening. The experience still fresh for him, upon their return from the evening he noticed cockleburs attached to his dog's fur. The design problem and the bio-inspired solution both showed themselves in a matter of hours.

These hooks and loops on the cocklebur proved tenacious. Upon inspection it was apparent that it maximized the number of spines on the bur to make attachment more 'probable'.

From the moment of discovery to analyzing the microfabrication under his microscope, it took many years and a considerable amount of work to develop a viable process for manufacturing the technical equivalent.

As time went by Velcro crept onto the market place due to its remarkable utility. Though, it is the bio-inspired approach that is the real innovator as it continues to develop a wide taxonomy of Velcro products.

Today the Velcro Companies Innovation and Technology Center is an international organization that caters to the demands of a global marketplace through product and process development in woven and knit textiles, continuous plastic molding, non-woven loops, and a variety of other fastener technologies.

As pioneers in hook and loop fastener technology, Velcro is the original patent holder of U.S. Patent 2,717,437 filed on October 15, 1952. Today, the Velcro Companies "strive to be the dominant innovator in fastening technology through efficient and creative solutions." They withhold over 300 active patents worldwide and have more than 50 years of experience developing hook and fasteners.

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Interdisciplinary Contribution

Bio-inspired design does not discriminate between disciplines. Most biomimics come from the fringes of their disciplines. George De Mestral was an Electrical engineer. To develop Velcro into what it is today it has taken scientists, businessmen, and engineers alike to ensure its success.

Inspiration can come from the most unexpected areas and at the most unexpected time. As is the case with Velcro. It is this lesson we learn that Bio-inspiration isn't just interdisciplinary, this and other cases of discovery suggest it is almost non-disciplinary. Nature surrounds us and so does our man-made world. The latter is the cause for many of our problems. The former, if noticed, can give us the solutions.

The Velcro venture has been a long process with ups and downs, that, only with the use of a collaborative approach could it be so successful. Today Velcro is a multi-million dollar industry. Construction engineers, astronauts, sports equipment designers, textile designers, and industrial designers of all sorts are utilizing the technology to design new uses for this half-century year old product.

Social Contribution

Everybody can relate to Velcro. Many straps for varying functional objects utilize this innovation. Adults remember the day when they were able to slip, so carelessly, in and out of their running shoes when they were very active as a child. Today, one can still experience that practical pleasure in many different brands of shoe.

Think of the useful applications in ones bike helmet and its removable padding. Sports gear, or the removable seat under you. The uses or innumerable. Though its use has made many users lives easier it is perhaps the name that most everybody relates to: *Vel*ours is a pile-woven fabric with threads to produce an upstanding fringe or pile. *cro*cet is a thread made up into a patterned fabric. bylooping yarn with a hooked needle.

Today, Velcro USA Inc. is a leader in the industrial, consumer, military, automotive, construction, and personal care markets with fastening innovations such as ULTRA-MATE® plastic HTH, VELTEX® display fabric, ONE-WRAP® straps, STICKY BACK™ tape, clear hook, non-woven fabrics, and many other re-closable fasteners.

This is a case of an extremely successful bio-inspired product. Other bio-inspired products touch our lives everyday. The social impact is great and increasing furthermore as engineers realize there is more to discover than invent. The story of Velcro is just one example of bio-inspiration wherein ecology meets product design. This principle has infiltrated such industries as agriculture, medicine, materials science, energy, computing, and commerce.

Design For a Living World
Material Conservancy
Project

Carleton University
Masters in Interdisciplinary Design
IDES 5201
Lorenzo Imbesi
Peter Wehrspann

Project Details

Institution:Cooper-Hewitt Design Museum
Contributors:Hella Jongerius, Maya Lin, Christien Meindertsma, Isaac Mizrahi, Abbott Miller, Ted Muehling, Kate Spade, Ezri Tarazi
Date:January 2010
Keywords: materials, furniture, sustainability
Website:www.cooperhewitt.org/exhibitions/Design-for-a-Living-World/

An installation at Smithonian's Cooper-Hewitt Design Museum showcased the work of ten leading designers who had been commissioned to "develop new uses for sustainably grown and harvested materials in order to tell a unique story about the life-cycle of materials and the power of conservation and design." The exhibition is co-curated by renowned graphic designer Abbott Miller and Ellen Lupton, curator of contemporary design at Cooper-Hewitt.

In May 2009 the exhibition debut venue was held. It then went on national tour, organized by The Nature Conservancy.

Innovation

This project is innovative on two different levels. The first level is that of material exploration in respects to energy conservancy and sustainability. The second level is that of affecting awareness and perceptions.

The 10 designers involved explored ecologically friendly materials--on several different levels--from unusual sources and locales to design concept products. The most important criterion was that each material was harvested sustainably and it contributed to the product life cycle that the biomimetic ethos transmits. Some of these materials include chicle(gum), salmon skin, normally discarded wood, wool, and ivory. These materials are well-known especially to indigenous craftsman who work with them to support local economy. It is the incorporation of these old school materials and techniques into the modern industrial paradigm that makes this project so innovative. Doing so, they explore formal possibilities with the ethics of conservation.

This project helps to redefine and promote a new definition of 'materials'. Its conceptual and exploratory nature promotes an increased awareness of natural resources along with a heightened sense of interest.

Curated as an art/design exhibition it first holds the attention, and then informs the general public.

Original perceptions about where materials are found, resource yields, energy conservancy, localization, and chemical use are challenged as these designers use innovative product design to connect people, place, economy, materials, and environment. Embracing otherwise foreign materials, the project refocuses our attention to the natural world.

Interdisciplinary Contribution

This project concerns itself with geographical, political, and cross-cultural collaboration. As the designers mostly prevail from Europe and the United States they needed to be concerned with issues of cultural norms, language, local perceptions and techniques. It is this cultural collaboration that gives weight to such an exploratory project. The products developed within this project have success to varying degrees. Though it is not the success of the individual objects that this project is most concerned with. Merging local craftsman, there techniques, tools, and materials with developed industrial systems is what is at the forefront.

The designers had to act as technical interpreters to focus and translate indigenous information about the details of a certain material or technique into a process or product that could be developed utilizing familiar tools of their home industrialized nation.

As networks develop and products born from this project become realized, one can see how economists, policy makers, and anthropologists become of increasing importance to such an undertaking.

Social Contribution

Increasingly the public and business is recognizing the dependence our economy and standard of living have on the environment and its resources. This project was able to be innovative with new materials while subsequently adding to the dialogue of economy, product, design, and material conservancy.

Maya Lin's work with what used to be discarded wood products is an example of productively redefining material utility. By embracing the imperfect parts of wood she helps to push aesthetic boundaries and thus concepts of sustainability. Through her furniture users are made aware of such issues.

Hella Jongerius reconstitutes the white milky substance from chicle trees to create hollow-ware that is both sustainably harvested, functional, and visually unique.

Abbot Miller's work with the Bolivian furniture industry is both culturally and technically innovative. Merging old school techniques with modern CNC technology the outcome is a chair that is culturally relevant and maximizes material usage and energy conservancy.

A curated project becomes a great medium for social, environmental, and economic change. Though, it is the eventual adoption and use of these products--which are now largely conceptual--that will truly innovate the entire culture that surrounds consumerism. People are urged to be ethical in their buying decisions as the messages of bio-compatible materials and products become socially pervasive.

Biologically-Inspired Innovation in Engineering Design
A Cognitive Study
Research

Carleton University
Masters in Interdisciplinary Design
IDES 5201
Lorenzo Imbesi
Peter Wehrspann

Project Details

Institution:Geoirgia Tech University
Authors: Swaroop Vattam, Michael Helms, and Ashok K. Goel
Date: April 2007
Keywords: Biologically-inspired design, Biomimetic Design, Biological Systems, Engineering Design, Interdisciplinarity
Website:www.cbid.gatech.edu/history.html

Biologically inspired design makes use of analogies derived from nature to solve engineering problems. It is an interdisciplinary field that faces challenges in understanding, learning, and the practice of its approach. Researchers at Georgia Tech's CBID observed and analyzed, interdisciplinary teams practicing their specific brand of BID. The report analyzes the observations in respects to theories of design and modeling.

Innovation

Historically, the transfer of biological information is proven to benefit technological growth in engineering design. This particular research is valuable for future growth as it seeks to understand the cognitive basis of biologically inspired innovation within the field. This report also illuminates the challenges and opportunities to enable more effective learning of such information. Furthermore, it examines applications of visual and computational tools that might foster the exchange and understanding of critical information between fields.

As society and industry move forward at a rapid pace, so too does scientific discovery. This novel scientific information represents a wealth of insight that may be applied to human and environmental problems. This report points to challenges facing its application. These are:
i)Organization of an incredible amount of biological information which grows in volume rapidly.
ii)Communication between engineers and scientists.
iii)The transfer of complex biological knowledge into engineering applications.

After analysis, the BID approach recognizes effective techniques employed by the instructors and students involved in the process to combat such challenges. The report suggests that we must innovative aspects of the BID approach to be successfully innovative with the outcome.

The approach details an iterative hierarchal process. The problem is first, defined, then 'biologized'. Solutions are rendered then evaluated. A visual model for deeper understanding is created and a design trajectory is confirmed.

Effective observation of such approaches can create opportunities for improving understanding of biologically inspired design and greatly affect technological innovation.

Biologically-Inspired Innovation in Engineering Design

A Cognitive Study
Research

Carleton University
Masters in Interdisciplinary Design
IDES 5201
Lorenzo Imbesi
Peter Wehrspann

Interdisciplinary Contribution

The CBID believes that science and technology has a limit to the approaches offered by traditional disciplines. For this reason Georgia Tech has created its interdisciplinary research curriculum. Within the BID approach, physical scientists, engineers, and interdisciplinary biologists collaborate and offer their resources, operating methodology, and knowledge to form solutions based on the principles of nature. Their intention? To facilitate research and education towards innovative techniques and products based on biologically inspired design solutions.

This report suggests biological information represents an untapped resource for not only design principles, but also uncommon methodology and concept-testing not currently utilized to its full potential in the field of engineering design. It seems as though while the fields of science and design merge at its boundaries, new opportunities become numerous in existence.

As these new opportunities increase there is a increasing need for organizational tools. This report stress's the integral role computer scientists play to create computational tools for visualization and organization.

This report was only made possible due to an interdisciplinary team and gives acknowledgement to the varying disciplines within Georgia Tech including: School of Chemistry, School of Polymers, Textile and Fiber Engineering, School of Systems and Industrial Engineering

Social Contribution

The CBID encourages biologically design driven approaches not only for the service of industry but also for the service of man and nature. Taking inspiration from nature as a source for innovative principles forces researchers and the people affected by the research to respect the natural world through preservation, and not, just 'harvest' its products.

Contemporary social well-being is heavily dependent on a healthy economy and a healthy natural environment. Our economy relies intemperately on the use of natural resources which continues to degrade the quality of our environment. Once the well runs dry, social unrest becomes a likely outcome. For that reason, this report is integral to the dialogue that concerns all members of society.

This research offers insight into the growing principles and opportunities of BID that represent the best solutions for supporting our environment. Whilst, continuing to 'fuel' the product innovation that our economy depends on.

As computational tools begin to help engineer designers sort and understand biological information, the general public may get close to reaping the benefits of such a tool. BID computational tools that are parsimonious in nature may indeed help the public solve problems in a way that benefits them and respects nature.

APPENDIX B

ORAL QUESTIONNAIRE

Probing Questions:

1.In two sentences could you describe what your organization is all about?

2.When discussing your field do you prefer to use the term bionics, bio-inspired, or biomimicry? Could you briefly explain your answer?

3.In your opinion what organizations are doing important work within your field currently?

4.Could you briefly explain some of your current research or projects?

5.Where do you see the future of the field in respects to: Products? Research? Industry? Education? Sustainability?

6.Is sustainability at the root of your efforts?

7.What hurdles to you see to interdisciplinary design efforts?

8.How do you suggest we overcome these hurdles?

9.The Biomimicry Institute (Add Respective Institute) recognizes three different levels of bio-inspired design: products, systems, and strategies. In your opinion is this categorization an effective approach?

10.In your opinion what do you see as the main difference between metaphoric bio-inspired design and direct bio-inspired design?

11.Could you briefly explain problem-based versus solution-based bio-inspired design?

12.Do you have strong opinions on how biomimetic concepts should be communicated to students?

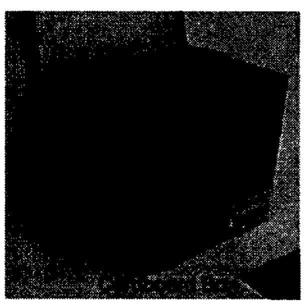
APPENDIX C

2D TOOLKIT/ENVIRONMENT

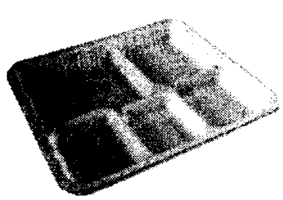
Examples Of Biodegradability In:

Furniture Design

Used in packaging. Takes up to 500 years or more to biodegrade, if ever.



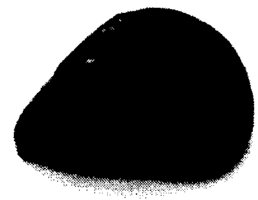
Cardboard used for packing furniture products can take only 2-5 months to biodegrade.



Plastic Tray

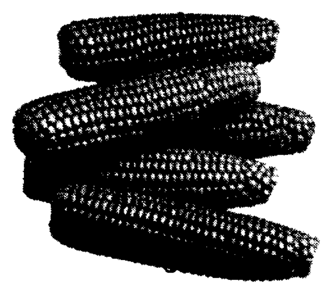
Take up to 500 years to biodegrade. New plastics can degrade into smaller particles but can not fully biodegrade.

Biology



Mussle

Some of natures structures don't biodegrade.



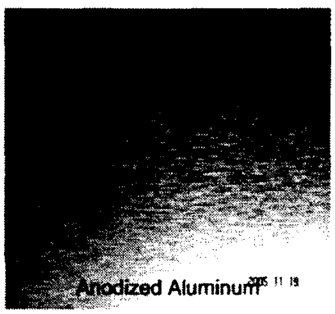
Biodegrades from 5 days to 1 month, depending on exposure to heat and oxygen.

Leaves can take approximately 1 year to biodegrade.

Examples Of Surface Treatments In:

Furniture Design

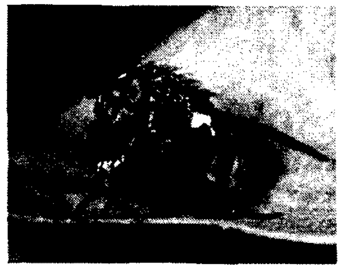
A very common furniture coating is an exterior coating such as latex paint or lacquer.



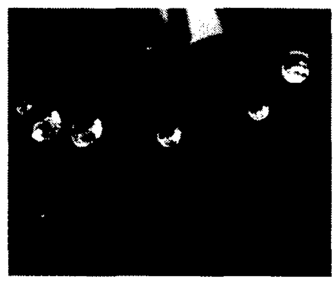
Increases corrosion and wear resistance and provides a good surface for adhesion.

Water resistant

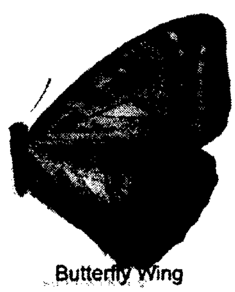
Biology



Flesh flies have hairs covering their bodies which act as repellers of bacteria.



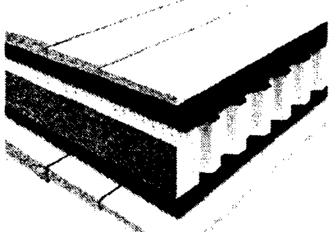
Tiny hairs or wax don't allow water to settle. This hydrophobic surface has self-cleaning properties.



Micro layers are iridescent. They refract light to give colour without pigment.

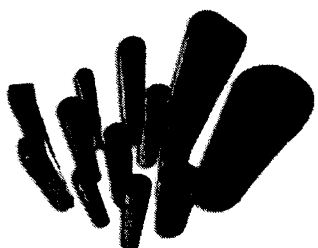
Examples Of Light, Strong Structures In:

Furniture Design



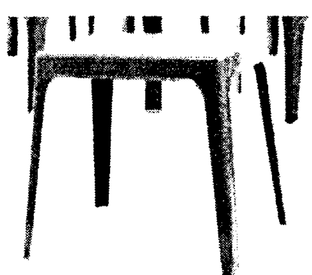
Lightweight Panels

A corrugated interior and sheeting exterior.



Steel Tubing

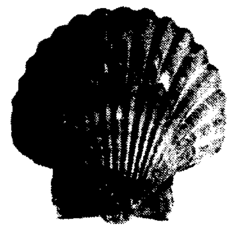
Material clear of the center ensures a stiff and light structure to prevent bending.



Moulded Plastic Tables

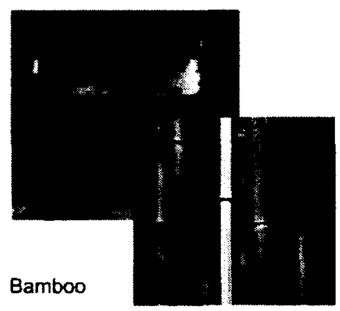
Half tube plastic legs create a cheap solution for a strong and light structure that achieves flexibility without stress.

Biology



Scallop

Pleats run along the direction that the surface is most likely to bend to give strength.



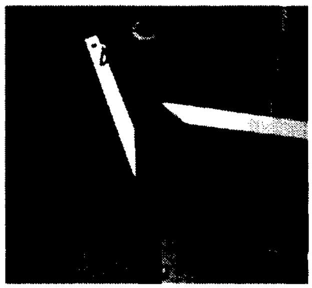
Bamboo

Flexural and torsional stiffness achieved by the use of punctuated hollow tubular elements.

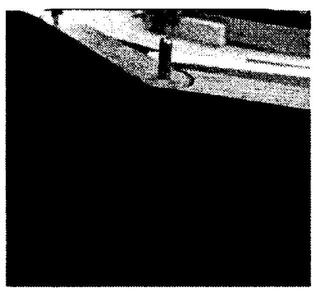
The stalk resists torsional forces with the use of a half tube.

Examples Of Flexible, Strong Joints In:

Furniture Design



Rotating metal joints provide solutions for flexible, lightweight furniture.



Using a combination of wood and metal, joints can be robust and offer some degree of flexibility.

Ikea Leg

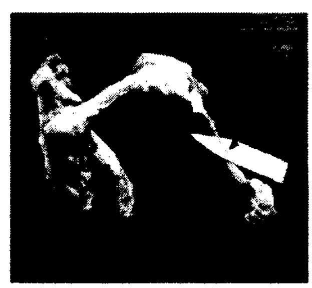
Flexible because they can be exchanged with ease. Require fasteners and does not deal with some forces well.

Biology

Insects have exoskeletons that join with soft tissues to create flexible protected joints.

Lobster Claw

Anthropods use similar structures to achieve strong and protected flexible joints.

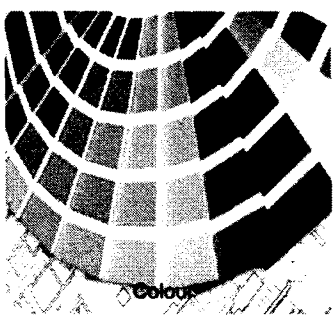


Like humans, animals have strong flexible joints that rely on ligaments to interconnect bones.

Examples Of Customization In:

Furniture Design

Different sizes are required to meet market demands of function and space.



Furniture products are available in different colours and materials to suit differing aesthetic tastes

Differing forms inspire different reactions to suit specific environments and tastes

Biology

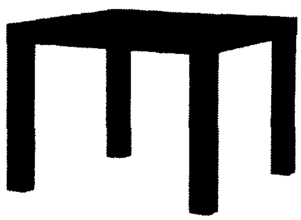
Adapts to the forces exerted on it to increase or decrease in mass to suit its structural function.

Renowned for its ability to adapt and thrive using organisms in its vicinity and local conditions.

Small pieces of wood are turned into paste to build the walls of its nest customized to its surroundings

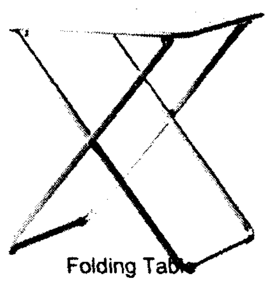
Examples Of Collapsibility In:

Furniture Design

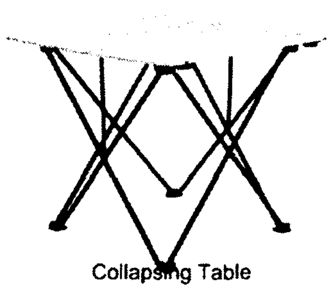


Ikea Table

Legs detach for packaging, shipping, and each assembly.

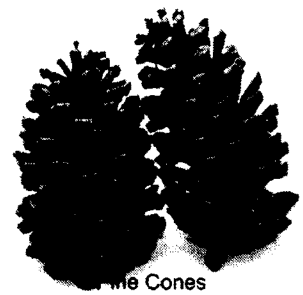


Some designs fold up simply on one axis with the removal of a certain part.

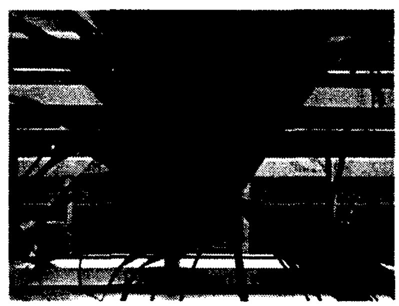


Specialized hardware and multiple axes to fold, designs achieve a high degree of collapsibility.

Biology



Flaps open up to release their seeds.

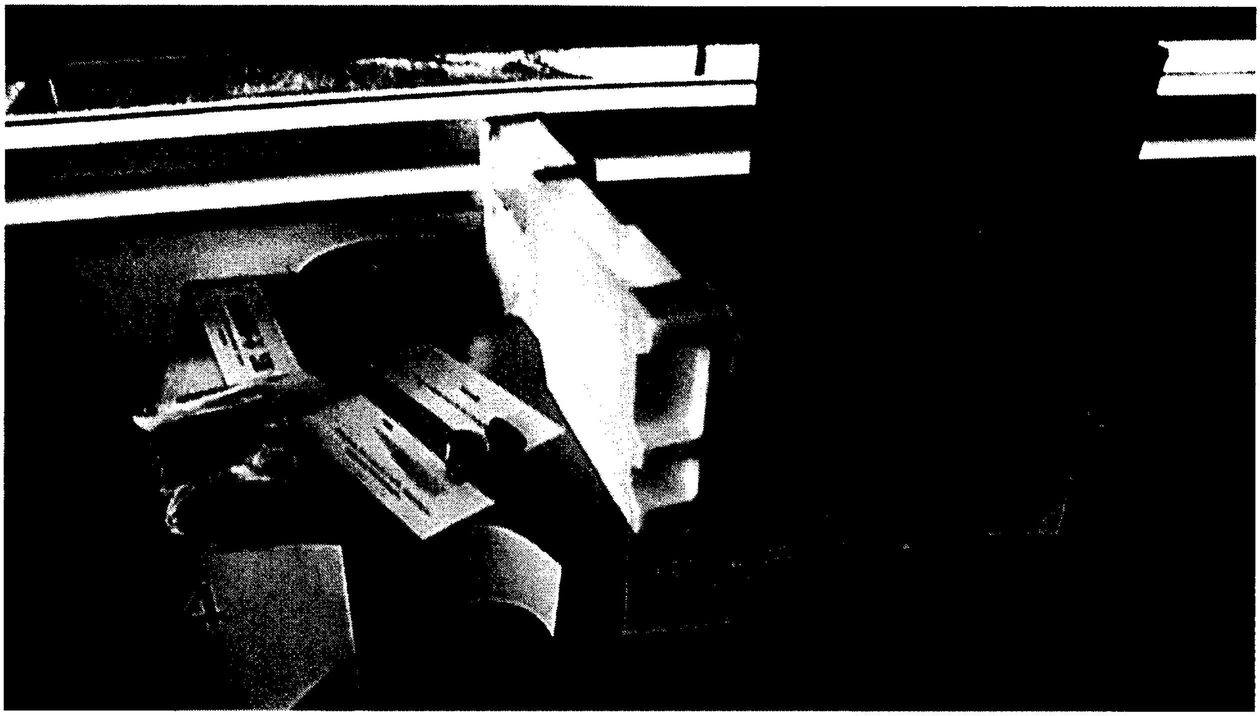


Relies on creases for unfolding into a large sun catcher. All creases share the same origin.

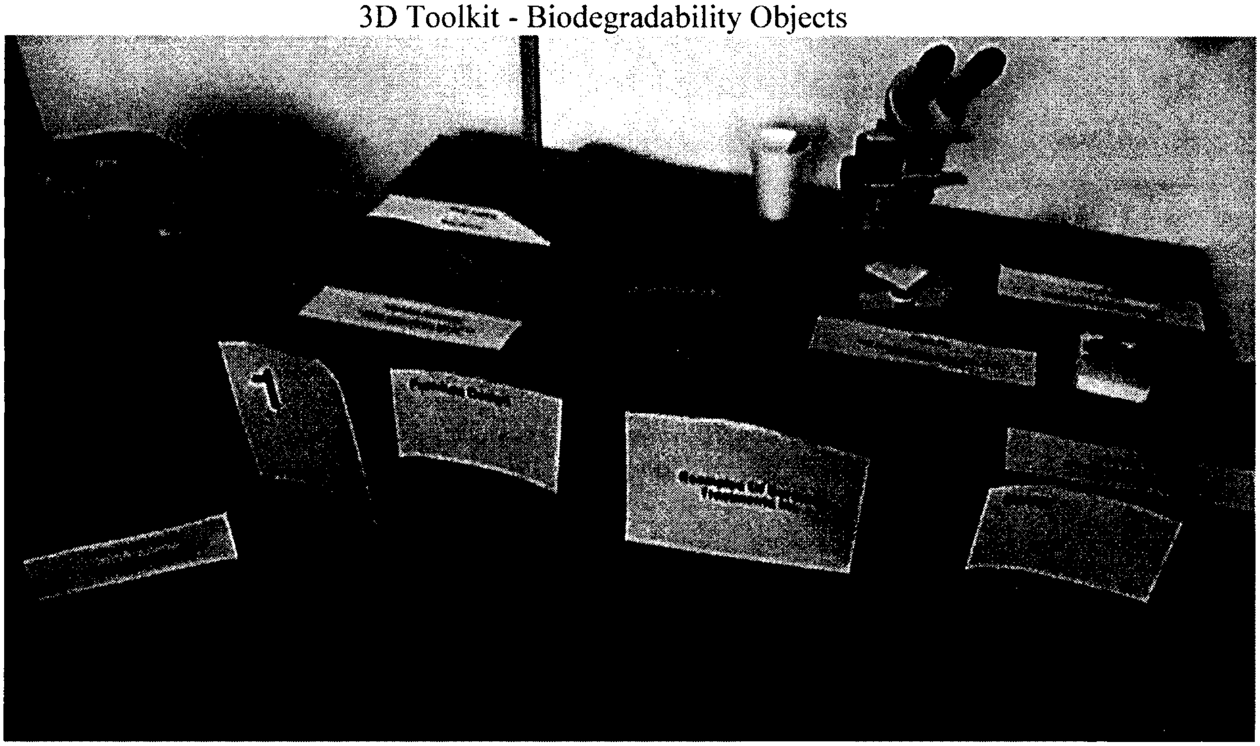
Wings fold under protective covers when on the ground. They can be deployed in a hurry.

APPENDIX D

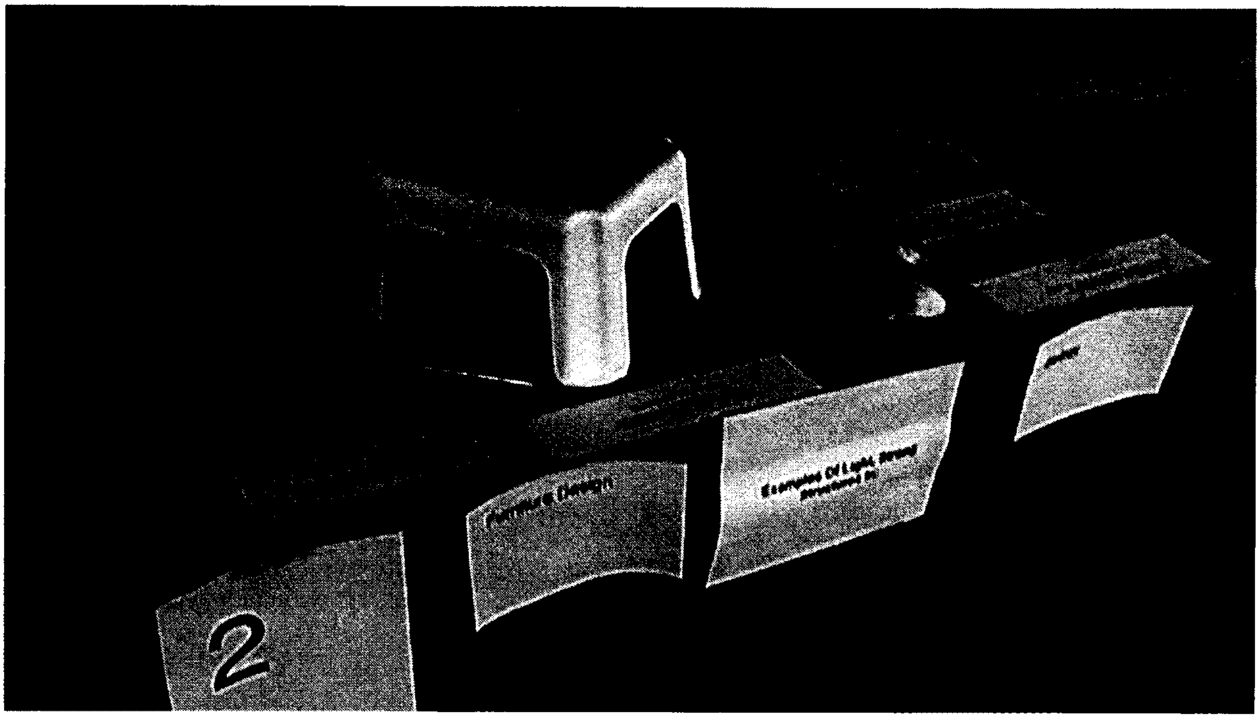
3D TOOLKIT/ENVIRONMENT



3D Toolkit - Biodegradability Objects

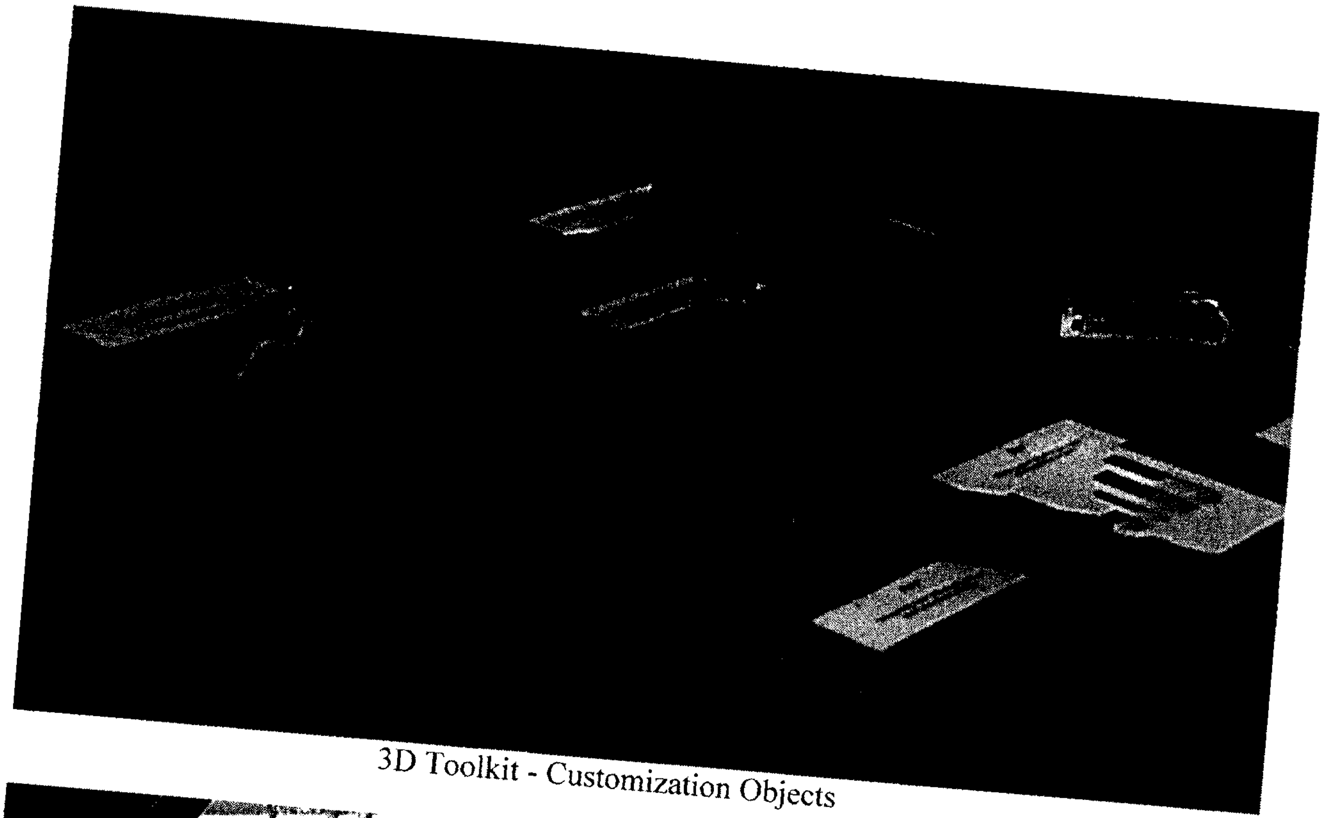


3D Toolkit - Surface Treatment Objects

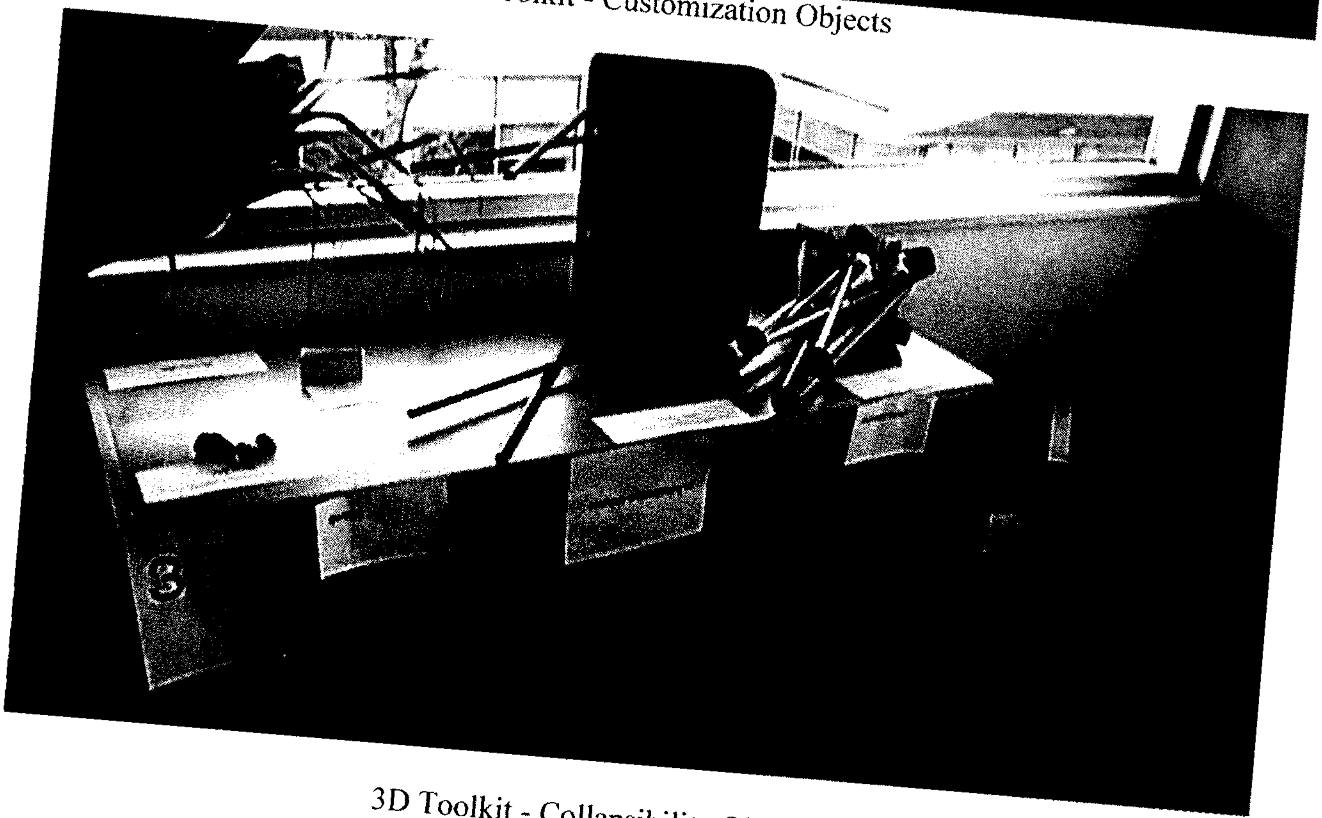


3D Toolkit - Light, Strong Structures Objects

3D Toolkit - Strong, Flexible Joints, Objects



3D Toolkit - Customization Objects



3D Toolkit - Collapsibility Objects

APPENDIX E

TEST ITINERARY

Itinerary

Welcome, Consent, Biology Independent Questionnaire

Purpose

1)biomimetic furniture for sustainability and innovation in these areas
- -Strong and Flexible Joinery
- -Strong and Light Materials
- -Biodegradability
- -Collapsibility
- -Customization
- -Surfacing

2)Develop a process to facilitate knowledge transfer between disciplines

3)evaluate my approach to develop this process by evaluating how well you retain and how much you've been inspired

Pre-Survey(no challenge only multiple choice)

Said before Enter Environment:

"Once you've entered you are challenged to learn and be inspired by all that you see and hear because you will be asked to recall what you have retained to complete the challenge after we exit."

-"You will have 2 minutes at each station to take in the information. On my mark you will move to the next station upwards from yours. When we enter please choose a station to start at. No note taking."

Once in the Environment:

-Intro to Biomimicry, Definition: "It is the copying of, use, or being inspired by, a biological organism, system, or concept to find solutions for manmade problems." Examples: Velcro, Gecko Tape, Kevlar

Rules: No taking notes

Post-Survey

Challenge

-Given after the multiple choice post survey

-Timed at 10 minutes

-Collection

Debrief

-Thank you

-Request that they do not share there experience with others so the study is not compromised.

-Gift cards

APPENDIX F

SURVEYS

Survey Questions

ID#:

1.Using the terms on the right place the corresponding number beside the biological examples you feel endows that characteristic. (Note: All terms do no have to be used). Terms may be used more than once. One example may endow more than one characteristic.

Scallop Shell	1-resilient
Butterfly Wing	2-water resistant
Lotus Leaf	3-cleanable
Lobster Claw	4-multiple purpose
Flesh Fly	5-durable
Ivy	6-scaleable
Bone	7-renewable
Wasp Nest	8-sustainable
Pine Cone	9-environmentally friendly
Beetle Wing	10-natural
Corn	11-engineered
Leaves	12-superhydrophobic
Palm Frond Leaf	13-strong and flexible
Palm Frond Stem	14-strong and light
Chicken Leg Joint	15-collapsible
Locust Leg Joint	16-biodegradable
Bamboo	17-iridescent
Mussel Shell	18-customized

2.Using the terms on the right place the corresponding number beside the furniture design examples you feel endows that characteristic. (Note: All terms do no have to be used). Terms may be used more than once. One example may endow more than one characteristic.

Custom Finish	1-resilient
PVC Fabric	2-water resistant
Cardboard	3-cleanable
Collapsible Table	4-multiple purpose
Custom Size	5-durable
Anodized Aluminum	6-scaleable
Folding Table	7-renewable
Custom Form	8-sustainable
Painted Steel	9-environmentally friendly
Plastic	10-natural
Styrofoam	11-engineered
Wooden Joints	12-superhydrophobic
Metal Joints	13-strong and flexible
Ikea Table	14-strong and light
Ikea Table Leg	15-collapsible
Steel Tubing	16-biodegradable
Lightweight Panels	17-iridescent
Plastic Outdoor Table	18-customized

3.List biological examples in regards to torsion?

4. List biological examples in regards to compression?

5. List biological examples in regards to tension?

6. List biological examples in regards to cantilever bending?

7. List design examples in regards to torsion?

8. List design examples in regards to compression?

9. List design examples in regards to tension?

10. List design examples in regards to cantilever bending?

11. What are the design properties important to furniture design?

12. What is about a scallop shell that addresses properties that are important to furniture design?

13. What about a locusts leg that may be applied to furniture design?

14. What similarities do you see between the surface of a leaf and anodized aluminum?

15. In terms of biodegradability what differences do you see between vegetables and biodegradable plastics?

16.How is bamboo similar or different than steel tubing?

17. Does corrugation occur naturally in nature?

18. Do mussel shell biodegrade?

19. Do bio-plastics biodegrade?

20. Why do we perceive butterflies to have colour even though they're wings do not contain pigment?

21. What are the similarities between ivy and a wasp's nest?

Share Your Experience

ID#:

1.I felt inspired from the exhibit. On a scale of 1-7 (1=not at all, 7=absolutely)
1 2 3 4 5 6 7

2.I felt like I learned something about biology. On a scale of 1-7 (1=not at all, 7=absolutely) 1 2 3 4 5 6 7

3.I felt like I learned something about design. On a scale of 1-7 (1=not at all, 7=absolutely)
1 2 3 4 5 6 7

4. Did it help you to re-enter the exhibit? Why?

5.How did the artifacts help you visualize design ideas during the design challenge? Briefly explain.

6. How will you use biology in the future to inform your design process?

APPENDIX G

DESIGN CHALLENGE

Design Challenge:

In the exhibit you were shown how furniture manufacturers currently deal with the following design criteria:

1. Strong and Flexible Joinery
2. Strong and Light Materials
3. Biodegradability
4. Collapsibility
5. Customization
6. Surfacing

You were also shown examples of how these are achieved in nature through the biological examples.

Now re-enter the exhibit to help yourself envision new ideas to address these design criteria. Design a table for a company like Ikea that involves as many of these criteria as possible. Attempt to incorporate at least 8 biological examples into your design. Use quick sketches and annotations(notes) to explain your ideas. Do not be concerned about aesthetics.

Use as much space as you need. Paper will be provided as you need it. (25 Minutes)