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BENCHMARKING BIO-INSPIRED DESIGNS WITH BRAINSTORMING IN TERMS OF NOVELTY OF DESIGN OUTCOMES

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ABSTRACT

With the increasing demand of innovative products in the market, there is a need for effective creativity approaches that will support development of creative design outcomes. Most researchers agree that novelty of design concepts is a major element of creativity; design outcomes are more creative when they are more novel. Biomimetics has emerged as a creativity approach that can lead to generation of novel design concepts. However, not many researchers explored how the degree of novelty of the concepts generated using biomimetic approaches compare with the degree of novelty of concepts generated using existing traditional creative problem solving approaches.

In this research we have compared the novelty of design concepts produced by using biological analogies with the novelty of design concepts produced by using traditional brainstorming.

Results show that there is an increase in the percentage of highly novel concepts produced in a design task, as well as the novelty of the concept space, when biological analogies are used over traditional brainstorming.

Keywords: biocard, biomimetics, conceptual design, creativity, novelty of concept space,

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1 INTRODUCTION

There is an increasing demand of innovative products in the market. This has oriented the focus of organizations to produce the products that have newness along with functionality as compared to the existing products. Organizations compete to produce innovative products so as to capture the market. This creates pressure on the designers to produce substantially novel designs of the products. For this, they rely on creativity approaches that can increase their chances of producing novel designs. So, the researchers are focusing on the efficacy of these creativity approaches and their influence on product designs. In this research, we have explored the influence of using biological and non-biological inspiration on the novelty of designs of the products. Our motivation behind this research is to develop more powerful techniques for supporting creativity in design.

2 LITERATURE SURVEY

2.1 Creativity and novelty: Definitions

Creativity is a mental process that involves generation of new and innovative concepts and ideas (Nguyen and Shanks, 2009). Pahl and Beitz (2007) define creativity as an inspirational force that generates new ideas or produces novel combinations of existing ideas, leading to further solutions or deeper understanding. The importance of creativity in designing products has been stressed by numerous authors (Gero, 1993, Chakrabarti et al., 2004, Chakrabarti, 2004). Organizations have also recognized the importance of human resources capable of creative thought as keys to better performance; creativity and innovation have gained significance for many organizations (Feurer et al., 1996).The term *creative* is also used in designating the innovative potential of products. Sarkar and Chakrabarti (2008) reviewed definitions of creativity and argued that the core elements of creativity are 'novelty' and 'usefulness', and a direct measure of creativity should be formed in terms of these two; they defined a creative product as one that is novel and useful. Chulvi et al. (2012) compared various measures of creativity and found novelty and usefulness as common elements across them. So, novelty is widely accepted as a major component for characterizing innovative and creative products.

2.2 Accessing novelty

With an increasing demand of creative products in the market, there is a need to identify or develop methods that can substantially enhance creativity of products. We assume that creative concepts lead to creative products. Creativity of concepts can be increased by increasing the novelty of concepts (Sarkar and Chakrabarti, 2011, Chulvi et al., 2012). So, by increasing the novelty of concepts, we aim to increase the creativity of the products.

2.2.1 Accessing novelty of a design concept

Sarkar and Chakrabarti (2011) reviewed existing methods of creativity assessment viz. Shah and Vargas-Hernandez (2003), Redelinghuys (2000), Chakrabarti and Khadilkar (2003), Lopez-Mesa and Vidal (2006).They took the inadequacies of these methods into account and proposed a new method for assessing the degree of novelty of design concepts. For validation, they benchmarked Shah and Vargas-Hernandez's (2003) method, Chakrabarti and Khadilkar's method (2003), and the method proposed by them, against the collective, intuitive notion of creativity held by experienced designers. They showed that the method proposed by them correlated strongly with the intuitive notion of designers as against Shah and Vargas-Hernandez's (2003) method, Chakrabarti and Khadilkar's method (2003). So, we have chosen this method for the evaluation of novelty in our research.

This method uses SAPPhIRE model of causality (Chakrabarti et al., 2005) to describe concepts in order to evaluate their novelty. The constructs of this model are (Srinivasan and Chakrabarti, 2009) from the lowest to the highest level are:

1. *Parts*: physical elements and interfaces system and environment that constitute the system.
2. *oRgans*: properties and conditions of system and environment required for interaction.
3. *Effect*: principle that governs interaction.
4. *Phenomenon*: interaction between system and its environment.
5. *Input*: physical quantity (material, energy or information) that comes from outside the system boundary, and is essential for interaction.
6. *State change*: change in property of the system (and environment) that is involved in interaction.

7. *Action*: abstract description or high-level interpretation of interaction.

Srinivasan and Chakrabarti (2010) describe this model as follows: Components and interfaces that comprise a system and its environment (parts) have some properties and conditions (organs). When the system and the environment are not in equilibrium with each other, there is a transfer of a physical quantity in the form of a material, energy or signal (input) across the system boundary. This physical quantity in combination with relevant properties and conditions, together activate a principle (effect). This principle is responsible for an interaction (phenomenon) between the system and the environment. The interaction between the system and the environment changes various properties of the system and the environment (state change). The change in properties can be interpreted at a higher level of abstraction (action).This model of causality built upon the above constructs and links is called SAPPhIRE model; the acronym SAPPhIRE stands for State-Action-Part- Phenomenon-Input-oRgan-Effect. See Figure 1.

Sarkar and Chakrabarti, (2011) argue that a product which is different from existing products at a higher level of SAPPhIRE constructs is more novel than a product that is different from existing products at a lower level of SAPPhIRE construct. Figure 2 shows the steps proposed by them for assessing novelty.

2.2.2 Assessing novelty of a Concept Space

Srinivasan and Chakrabarti (2010) proposed a method for computing the novelty of a *Concept Space* (CS). They defined a *concept* as an entity, which is a collection of ideas at the various levels of SAPPhIRE abstraction that satisfy an overall function. An *idea* is defined here as an entity at a particular level of SAPPhIRE abstraction. A CS for a function is a collection of alternative concepts that satisfy the function. A *New Concept Space* (NCS) is a set of all concepts, produced in a design process by a designer or a team of designers, which satisfy a given function. The novelty of an NCS is calculated as the average of novelty values of the all the concepts in the NCS. To assess the novelty of a concept in the NCS from a design session, it is compared with the existing concepts that comprise the *Existing Concept Space* or ECS, and the concepts that are generated earlier in this design session. The SAPPhIRE constructs of each new concept is compared with the SAPPhIRE constructs of the ECS and the design concepts generated earlier in the NCS. Depending on the highest level of SAPPhIRE abstraction at which an idea constituting the new concept is different from those in the ECS and those generated earlier in the design session, a number rating between 1 and 7 is used as novelty score. Here 1,2,3,4,5,6,7 are the number ratings given respectively to part, organ, effect, phenomena, input state change and action. A value of 0 is assigned if there is no novelty i.e. if the SAPPhIRE levels of abstraction of the new concept are same as those in the ECS and those in the NCS generated earlier.

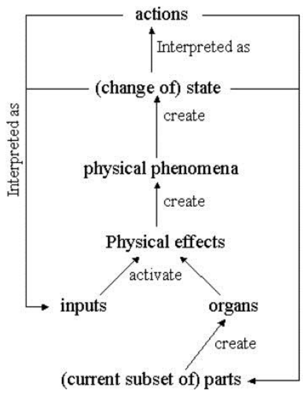

Figure 1.SAPPhIRE model of causality (Chakrabarti et al., 2005)

2.3 Analogy: Classification and its influence on novelty

Analogical reasoning has been accepted as an important means for novel idea generation (Darren and Moreau, 2002, Casakin, 2004). Researchers in design have classified analogy on the basis of the distance between the *source domain* and the *target domain*. Domain from where the analogy is drawn is the source domain. Domain to which the analogy is applied is the target domain.

Darren and Moreau (2002) quoted about 'far' and 'near' analogies as follows: Whereas some analogies may be drawn from knowledge bases that are similar to the target, other analogies may be drawn from bases that are "wildly discrepant" (Ward 1998, p. 221). Consequently, analogies are often described by their position on a continuum ranging from near at one extreme to far at the other (Gentner et al, 1997, Perkins 1997).

Casakin (2004) classified analogy using within domain and between-domain analogies. When an analogy is established between two different domains, each of which embrace dissimilar knowledge, but with a common shared correlation based on similar structural aspects, this type of analogy is known as 'between-domain'. Here, the source and the target problem belong to 'different and distant' domains. In cases in which source and target are embedded in the 'same or very close' domain, the analogy is called 'within-domain'.

Ward (1998) proposed that people should be able to develop more creative ideas by moving back up the path in conceptual hierarchy to more abstract levels. Moving back up the path might be thought of as enhancing originality by shifting the case from a near analogy to far one. Dahl and Moreau (2002) statistically proved the hypothesis that the higher the proportion of far analogies used in a design task, the greater the originality of resulting design concepts. Since originality accounts for novelty of design outcomes (Chulvi et al., 2012), we argue that far domain analogies influence creation of concepts with greater novelty.

2.4 Biomimetics as an Analogy from a Different Domain

We argue that as biological domain and engineering domain are different from each other, therefore, it can be hypothesized that engineering design outcomes that are inspired from biological domain will be more novel than design outcomes that are not inspired from biological domain.

Hesselberg (2007) reviewed various inventions from ancient times till recent ones that have used nature as a source of inspiration for solving design problems; this shows that nature has been used anecdotally throughout human civilization. However, using biological inspiration in a systematic manner is a relatively new domain (Chakrabarti et al., 2005).Biomimetic design has spawned innovation in design as well as pointed to ways of improving existing designs (Vakili and Shu, 2001).

Researchers agree that biomimetics has emerged as a creativity approach that can lead to generation of novel concepts. However, not many researchers explored how the degree of novelty of the concepts generated using biomimetic approaches compare with the concepts generated using existing creative problem solving approaches. Among existing creativity problem solving approaches, brainstorming is one of the most well-known (Fernald and Nickolenko, 1993, Isaksen and Gaulin, 2005). We take traditional brainstorming as a benchmark because brainstorming provides the best rated outcomes in terms of novelty over other methods like SCAMPER, Functional Analysis, etc.(Chulvi et al., 2012).

The overall aim of this research is to develop more powerful techniques for supporting creativity in design. The overall objective of this paper is to understand the relative efficacy of biologically inspired design approaches by comparing the novelty of designs of products inspired from biological domain to the novelty of designs of products inspired from traditional brainstorming.

A key challenge associated with analogical reasoning applied to biomimetic design is the extraction of strategies from biological phenomena relevant to the design problem (Shu, 2012).Biomimetic design uses biological phenomena to inspire solutions for engineering problems (Lenau, 2009). In this work, we provide biological information to the subjects in the form of *biocards*. A biocard is a representation of biological inspiration in a form that puts forth before the designers biological phenomena, biological mechanism and the functional principle behind the phenomenon (Lenau et al., 2010); Lenau et al. (2010) defined biological phenomena as any phenomenon occurring in nature; biological mechanism as how and why a particular phenomenon occurs in nature, and biological principle as the biological mechanism described in engineering terms. Figure 3 shows an example of a biocard.

3 RESEARCH OBJECTIVE

The objective is to assess the relative efficacy of biomimetic approach in producing novel designs using two methods:

1. To compare the novelty of *concepts* generated using biocards with using traditional brainstorming as a benchmark.
2. To compare the Novelty of the *Concept Space* generated by using biocards with using traditional brainstorming as a benchmark.

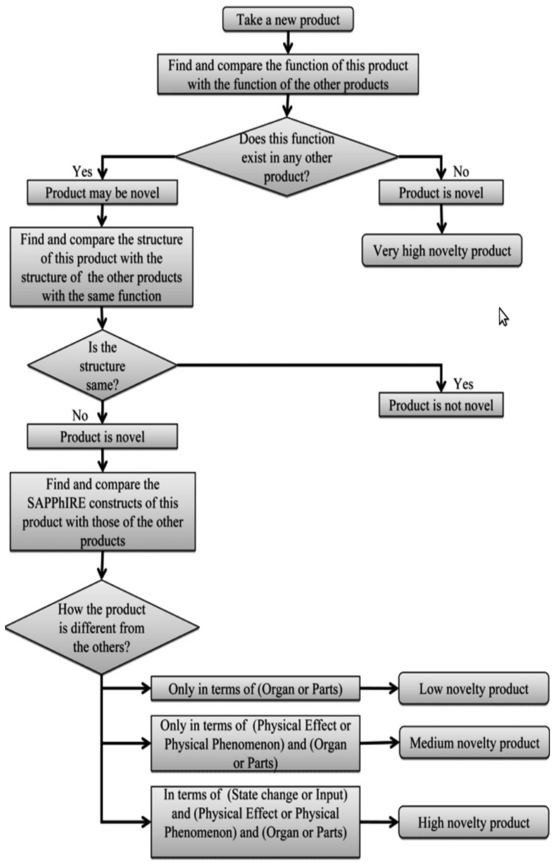

Figure 2. Steps proposed by Sarkar and Chakarbarti (2011) for assessing novelty.

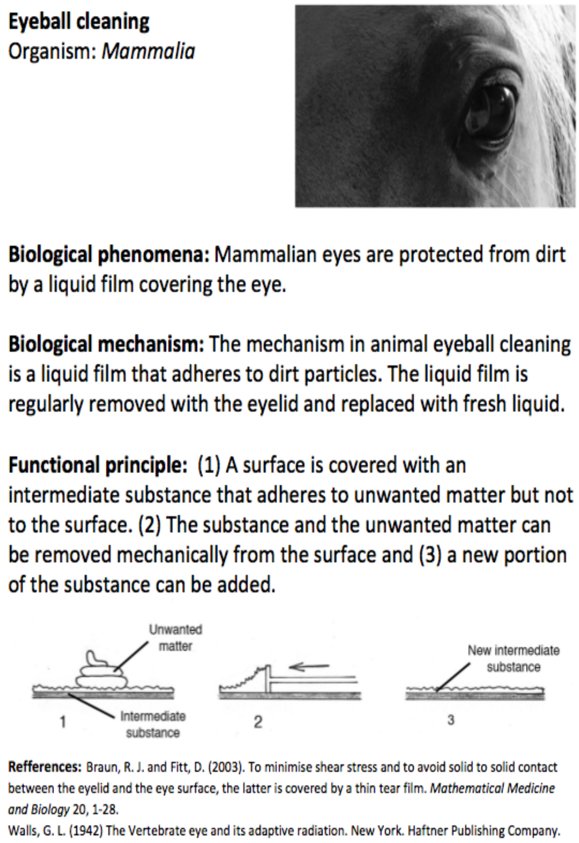

Figure 3. Example of a biocard based on the format proposed by Lenau et al., (2010).

4 RESEARCH HYPOTHESIS

The research hypothesis is the following: The novelty of design concepts generated by using inspiration from nature is greater than the novelty of design concepts generated by using traditional brainstorming.

5 EXPERIMENTAL PROCEDURE

This section presents the procedure of the experiments that were conducted to test the hypothesis. These experiments were conducted at two different places i.e. at Indian Institute of Science, India and at Technical University of Denmark, Denmark to verify the hypothesis across different cultures. Henceforth, we will mark the experiment conducted in India as 'Indian study' and the experiment conducted in Denmark as 'Danish study' in this paper.

15 novice designers were chosen as subjects for conducting the experiment in the Indian study. All the subjects were first year students of Masters in Design. 4 design teams were created randomly; Team 1, 2 and 4 had 4 members each, and Team 3 had 3 members. This limitation is attributed to the availability of subjects suiting to the requirements of the experiment. In the Danish study, 23 subjects were chosen for conducting the experiment. These subjects were the students of first and second year of master education in Technical University of Denmark. 4 Design teams were formed randomly. Teams 1, 2 and 3 had 6 members each and Team 4 had 5 members. This limitation is attributed to the availability of subjects suiting to the requirements of the experiment.

Following were the problems selected for the experiment.

A: To reduce the impact of physical collision. B: Windows that shade sun but allow the view.

The rationale behind selection of these problems was that the subjects should have some prior familiarity with issues around the problem so that they are able to generate the concepts within limited time and without using external source of information like internet during the experiment.

Table 1 shows the design of session 1.This session involved the following tasks.

Task 1: Each member in the team drew a description of the problem.

Task 2: Each team formulated the search terms on biological analogies and made a prioritized list.
Task 3: Each team described two of the analogies in the form of biocards.
In Session 2, Problem A was assigned to Team 1 and 2 and Problem B was assigned to Teams 3 and 4. See Table 2. This session involved following tasks.
Task 4: Each team brainstormed on the assigned problem and presented the solution as sketches.
Task 5: Each team used biocards produced by the other team in Task 3 to generate solutions and presented the solutions in the form of sketches.
There was no limit to the number of solutions that the teams could propose. All solution concepts had to be presented in the form of labeled sketches with other necessary details. The duration of each session was limited to 30 minutes, with 15 minutes of break between Task 2 and 3; and Tasks 3 and 4. It was an observational study with no intervention from the researchers.
It can be argued here that as the problem in Task 4 and Task 5 was same for each team, brainstorming in Task 4 can serve to train the participants to generate more novel concepts in Task 5 which can bias the results. However, one can expect less original solutions in Task 5 as participants become tired and start running out of ideas with time.

5.1 Data Analysis

The novelty of design concepts is evaluated for the concepts generated in both Task 4 and Task 5 for each team for both Indian and Danish studies. SAPPhIRE Model for the evaluation of novelty as proposed by Sarkar and Chakrabarti (2011) has been used for this purpose, see section 2.2.1. We categorize the design concepts generated in Task 4 and Task 5 as ‘highly novel’, ‘medium novelty’, ‘low novelty’, and ‘not novel’. Initially, we chose the number of highly novel concepts generated in a task as the unit of analysis in this calculation. This is because we intend to compare the number of highly novel concepts generated in Task 5 with the number of highly novel concepts generated in Task 4. However, as the total number of concepts produced in each design session is different (see Table 3 for example), we normalize this data by calculating percentage of highly novel concepts produced in a design task.

*Percentage (Highly Novel Concepts in Task A) = No. of Highly Novel concepts in a Task A/ Total No of Concepts in Task A * 100* (2)

The Novelty of Concept Space generated is evaluated using the method proposed by Srinivasan and Chakrabarti (2010), see Section 2.2.2. Novelty of Concept Space is computed by averaging the novelty score awarded to each design concept in a design task. So by using this method we ensure that we take into account the overall novelty of the concept space generated in a design task unlike in the previous method that give us only the percentage of highly novels ideas generated in a design task.
Following are the units of analysis of this study: a) Percentage of Highly Novel Concepts generated in a design task and b) Novelty of a Concept Space.

Table 1. Design of Session 1

Team	1	2	3	4
Problem	B	B	A	A

Table 2. Design of Session 2

Team	1	2	3	4
Problem	A	A	B	B
Biocard from	Team 3	Team 4	Team 1	Team 2

5.2 Examples of Concepts Generated

Figure 4 and Figure 5 are two examples of solution concepts proposed for Problem A: Reduce the impact of physical collision. Figure 4 shows two colliding vehicles with springs attached to them in the front. Figure 5 shows a vehicle with a pressure sensor attached to its front bumper. The SAPPhIRE constructs of concepts in Figure 4 and Figure 5 are shown as Concept 1 and 3 respectively in Table 4. Concept 2 and 4 (Brown, 2005, Holden, 2012) are the existing concepts that matched with concepts 1 and 3 respectively at the highest level of SAPPhIRE construct. At the highest abstraction level of SAPPhIRE abstraction Concept 1 and 2 differ at the organ level. So, by using the method of Sarkar and Chakarbarti (2011), Concept 1 is a ‘low novelty’ concept. The highest level of SAPPhIRE abstraction at which Concept 3 and 4 differ is input level, so by using the same method, Concept 3 is a ‘High Novelty’ concept. The digits 1-7 in parenthesis in the first column of Table 4 denote the SAPPhIRE levels of abstraction.

Table 3. No. of Highly Novel and Total Concepts for Team 3 and 4 in Danish Study

Team No.	Team 3 in Danish Study		Team 4 in Danish Study	
Task	Highly Novel	Total Concepts	Highly Novel	Total Concepts
Task 4	1	7	1	9
Task 5	3	3	2	4

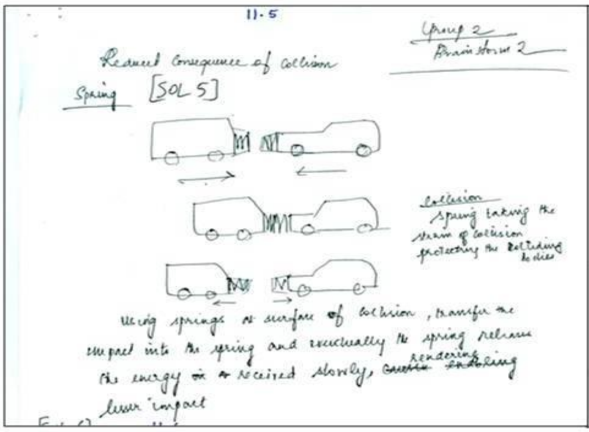

Figure 4. Concept 1 generated for Task 4

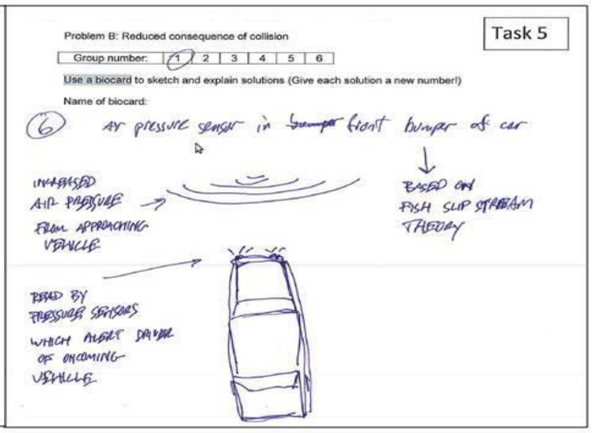

Figure 5. Concept 3 generated for Task 5

Table 4. SAPPhIRE constructs of Concept 1 and 3 compared with Existing Concepts 2 and 4

Concept No.	1	2	3	4
Task	Task 4	Existing Concept	Task 5	Existing Concept
Function	Reduce the impact of physical collision			
Behavior	Springs come in contact with the colliding body first and compress upon collision	Bumpers deform plastically to absorb energy of collision. Less energy is transferred to auto parts.	As the vehicles draw near, air velocity between them changes and so the pressure. Pressure difference is sensed by alarm. Driver becomes alert.	Parking sensors emit ultrasonic waves that hit the obstacles in the path. Sensor detects waves reflected by the obstacle. Alarm rings. Driver becomes alert.
Structure	Springs attached at the front of the vehicle	Bumper made of softer material mounted at front and the back	Vehicle with pressure sensor mounted on front bumper.	Vehicle with ultrasonic parking sensor mounted on front and rear bumpers.
Action (7)	Reduced impact of collision on the vehicle.	Reduced impact of collision on the vehicle.	Driver is alerted about collision	Driver is alerted about the collision.
State Change (6)	From high energy to low energy transmitted to passenger cabin.	From high energy to low energy transmitted to auto parts.	From No signal to danger signal of danger alarm.	From No signal to danger signal of the alarm.
Physical Phenomena (4)	A fraction of KE of the vehicle is converted into strain energy of the spring.	A fraction of KE of the vehicle is converted the plastic strain energy of the bumper.	Change in air velocity creates pressure difference.	Waves hit with the objects in the path and are reflected back. The reflected waves are detected.
Physical Effect (3)	Strain energy of spring = $\frac{1}{2}$ k x^2=Fraction of KE of colliding vehicles.	KE =c. Plastic Strain energy of bumper, c= some constant	Velocity is inversely proportional to Pressure	Distance between obstacle and vehicle d= f(v, t, x) v = speed, t = time

				between emission and detection of waves, x = other variables
Organ (2)	Stiffness of the spring should be high to absorb Kinetic Energy	Bumper should deform plastically	Alarm should ring if the pressure difference is not within the specified limit.	Alarm should ring if the distance between the obstacle and the vehicle is less than a specified limit.
Input (5)	Kinetic Energy	Kinetic Energy	Air Pressure	Sound Energy
Part (1)	Springs attached to the front of the vehicle	Bumper made of plastic material attached to the front and back of vehicle	Vehicle with pressure sensor mounted on front bumper.	Vehicle with ultrasonic parking sensor on front and rear bumpers.

6 RESULTS

6.1 Comparison of novelty of design concepts

In this section we present the comparison of novelty of design concepts generated by traditional brainstorming in Task 4 and by using biocards in Task 5. See section 2.2.1 for details.

Table 5 compares the percentage of highly novel concepts produced in Task 4 and Task 5 in Danish study. Except for Team 3, all other teams show an increase in the percentage of highly novel concepts in Task 5 over Task 4. Team 2 and Team 4 respectively show that 50 % and 57 % of the concepts generated in Task 5 were Highly Novel concepts ie. more than half of the concepts generated belonged to High Novelty category. It should also be noted that the average percentage of Highly Novel concepts in Task 4 is 30 % which increases to 44 % in Task 5.

Table 6 shows the results of Indian study. Teams 3 and 4 show an increase in the percentage of Highly Novel concepts produced in Task 5 as compared to Task 4. Note that Team 3 shows 100% highly novel concepts and Team 4 shows 50% of highly novel concepts generated in Task 5. Also, the average percentage of highly novel concepts produced in Task 4 is 20 % which increases to 44% in Task 5.

From this data, we interpret that percentage of Highly Novel concepts produced increases when biocards are used in Task 5 as compared to traditional brainstorming in Task 4.

6.2 Comparison of Novelty of Concept Space

In this section we present the comparison on Novelty of Concept Space for the concepts generated by traditional brainstorming in Task 4 and by using biocards in Task 5 for each team. See section 2.2.2 for details. Table 7 and 8 show the findings from this analysis for Danish and Indian study respectively. In Table 7, except for Team 3, all other teams show an increase in Novelty of Concept Space score in Task 5 as compared to Task 4. Also, there is a net increase of 3.37 in Novelty of Concept Space score of Task 5 as compared to Task 4. Similarly in Table 8, Teams 3 and 4 show an increase in the Novelty of Concept Space score in Task 5 as compared to Task 4. Also, there is a net increase of 5.93 in Novelty of Concept Space score of Task 5 as compared to Task 4.

From these findings, we interpret that the Novelty of Concept Space increases when biocards are used in Task 5 as compared to traditional brainstorming in Task 4.

7 DISCUSSION

Findings from the above analysis indicate that a higher percentage of highly novel concepts are produced when they are inspired from biological analogies with biocards as a means to provoke them over the concepts that are generated using traditional brainstorming. The Novelty of Concept Space also increases when the concepts are inspired from biocards used as a means of biological analogy. In a few cases, traditional brainstorming performs better over biocards. There may be various reasons for these results. Between the two assigned problems, one problem may be more explored over the other, and hence more saturated. Exposure of subjects to already existing solutions for the given problem might be another reason. The search for existing concept space for the purpose of evaluation of novelty was done through the internet. Though we made a thorough search, yet it cannot be exhaustive. Novelty values depend upon the exhaustiveness of existing solution space used in the calculation.

8 CONCLUSIONS

In first phase of this study, we benchmarked novelty of design concepts generated by using biological analogy with novelty of design concepts generated by using traditional brainstorming. The results show an increase in the percentage of highly novel concepts generated when biological inspiration in the form of biocards is used over traditional brainstorming, in most of the design sessions.

In the second phase of this study, we compared Novelty of Concept Space generated by using biological information with Novelty of Concept Space generated by using traditional brainstorming. The results show an increase in Novelty of Concept Space generated when biocards are used over the Novelty of Concept Space when traditional brainstorm is used. By using both the methods we have compared the occurrence of highly novel ideas generated in a design task and the overall novelty of concepts.

As similar results are obtained in both the Indian and the Danish study, we can argue that our conclusion is consistent across cultural differences. Team 4 in the Danish study and Team 3 in the Indian study are the groups that show remarkable leap in novelty values as compared to other teams. Factors that created this leap in novelty of design outcomes in these groups need to be further explored. Further work is also needed to ascertain how effective biomimetic approaches are, and the specific reasons as to why they are more effective.

Table 5. Percentage of Highly Novel Concepts produced in Danish Study

Task / Team	Team 1	Team 2	Team 3	Team 4	Average
Task 4	20	33	67	00	30
Task 5	43	50	25	57	44

Table 6. Percentage of Highly Novel Concepts produced in Indian Study

Task / Team	Team 1	Team 2	Team 3	Team 4	Average
Task 4	36	20	14	11	20
Task 5	25	00	100	50	44

Table 7. Novelty of Concept Space for Danish study

Task / Team	Team 1	Team 2	Team 3	Team 4
Task 4	3.20	3.33	4.17	1.25
Task 5	3.71	3.50	3.25	4.86

Table 8. Novelty of Concept Space for Indian study

Task / Team	Team 1	Team 2	Team 3	Team 4
Task 4	2.86	2.10	1.86	2.33
Task 5	2.75	2.00	5.33	5.00

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