BIOCARDS AND LEVEL OF ABSTRACTION

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Abstract

Biocards are formal descriptions of biological phenomena and their underlying functional principles. They are used in bioinspired design to document search results and to communicate the findings for use in the further design process. The present study explored the effect of abstraction level used in biocards. This was done in two workshops conducted with design students in Denmark and India. Students were given a design assignment and instructions for how to perform the BID ideation work. Half of the students were given biocards with abstract descriptions while the other half got biocards with concrete descriptions. The novelty of found solutions was evaluated by the students by rating novelty of each solution on a scale from 1 to 5. Mean values for abstract descriptions were 0,3 higher than for concrete descriptions indicating that more innovative solutions were found when students used biocards with abstract descriptions compared to concrete descriptions. The difference in mean value is significant with a confidence level better than 1%. It seems likely that more abstract descriptions in biocards helps avoiding design fixation in biomimetic design work.

Keywords: Bio-inspired design and biomimetics, biocards, abstraction level, analogical reasoning

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1   INTRODUCTION

In bio-inspired design (BID) a central element is searching the biological domain for functional analogies to a given design problem. Each analogy needs to be understood to a level allowing further design work. It has earlier been described how biocards can be used to assure a focus on functional principles and the right amount of information needed in the design process (Ahmed-Kristensen et al 2014, Lenau et al. 2011, Lenau et al. 2010). It has been shown that biocards helps to higher quality design solutions with respect to novelty (Keshwani et al. 2013). However an open question is if a high level of abstraction in the biocards will be an advantage or if it is more beneficial to keep descriptions concrete and closer to the biological domain. There is though a risk for design fixation (Jansson & Smith 1991) in describing biological analogies in terms close to biology, i.e. using concrete biocard descriptions. Describing a biological phenomenon in terms close to the natural reality will include a large amount of relevant and extra irrelevant information. There is a risk that the designer will focus on irrelevant parts of the description and seek solutions in other directions than was intended in the original problem formulation. A simple example is the design problem 'how to fly' or 'how to create a lift'. A very likely search result is birds that fly and a biocard could describe how a bird flies by spreading its wings. However a possible fixation (which was the case for many years) is to focus on how birds flap their wings. Even though this is part of the explanation for how birds fly, it is a wrong place to start, which many tragic accidents through history has shown. If instead the biocard was focused on the core functional principles that secure a lifting force the risk of fixation would be smaller. The use of analogies is recognised as phenomena that increases and can support novelty, with analogies from far domains (such as biology) likely to create more original solutions (Dahl & Moreau 2002, Ahmed & Christensen 2009). However, fixation is also a well-known problem in creativity, and the use of these analogies in creative brainstorming sessions implies that designer only be using these analogies and can be seen as encouraging fixation. Hence one research challenge is in identifying how best to present the analogies to support innovation whilst limiting the effect of fixation. In this paper we look at the role of biocards with abstraction, but the work could extent to presentation of other far domains analogies.
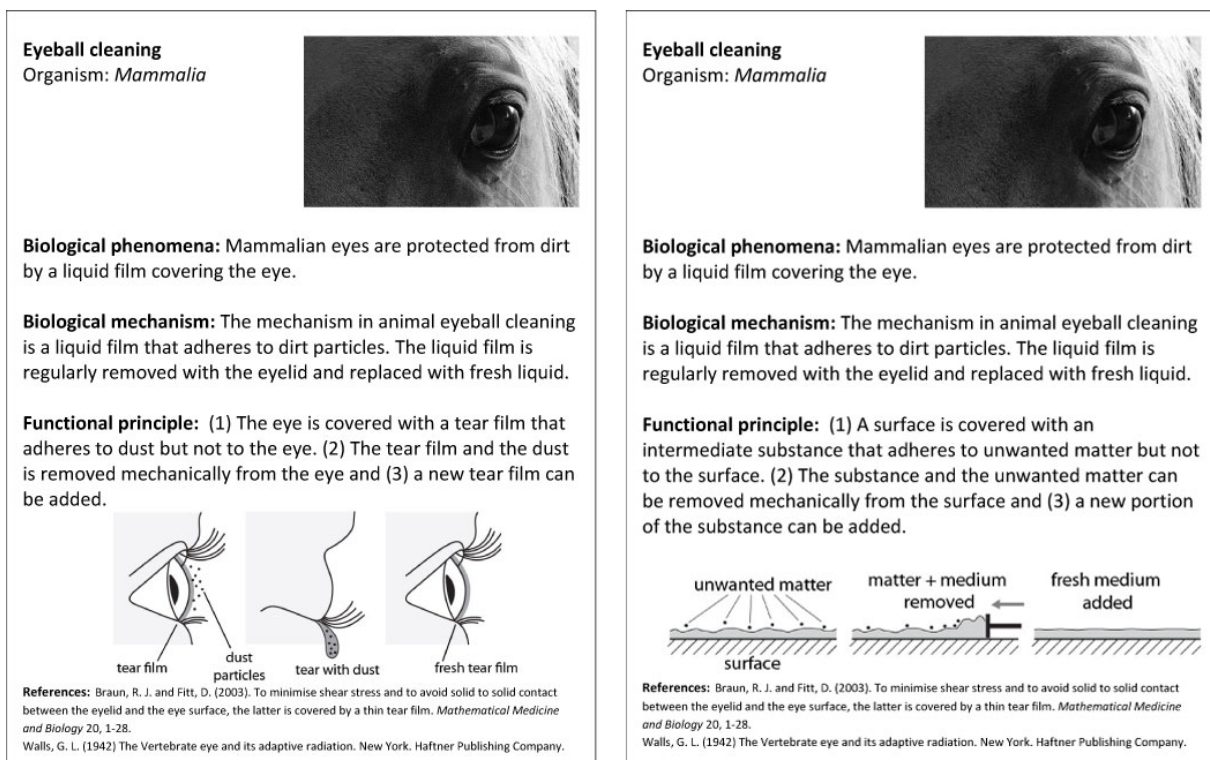

Figure 1. Concrete (left) and abstract (right) biocards.

Our claim is that it is important to formulate biocards with focus on abstract functional principles rather than concrete biological descriptions. One way of achieving this is as described on the biocards shown in Figure 1. Even though the two cards look similar the core message of the functional principle is different. The concrete biocard uses terminology from biology and describes the functionality as it works in the organism. The abstract biocard on the other hand uses a terminology closer to the engineering domain and avoids using terms that dictate a certain solution.

A counter argument to using abstract biocards could be that designers often have well developed abstraction skills which allow them to focus their design process even when supplied with ambiguous and unclear information. However our experience is that in particular engineering students have a tendency to fixate on the concrete biological description and in many cases have difficulties in making abstractions and following propose radical different design solutions. As an example will most engineers using the biocards in Figure 1 be able to propose a solution that uses water for keeping a surface clean but fewer will think about using other substances like gravel or sand that in principle can solve the same problem.

The present paper describes an experiment to investigate the effect of using abstract or concrete description of biological phenomena in biocards upon their solutions. The hypothesis we intended to examine is: More novel design solutions are likely to be found when biocards with abstract descriptions are used compared to biocards with concrete descriptions.

In workshops conducted with design students in Denmark and India the question was examined. In the workshops the students were given a design assignment and instructions for how to perform the BID ideation work. The students were told that the workshop had the purpose to teach them how to do BID ideation and that we collected their results in order to improve the methodology. However they did not know what we were looking for. Our results indicate that more innovative solutions were found when students used biocards with abstract descriptions compared to concrete descriptions.

The paper is organised as follows. First related work within biomimetic design and design fixation is reviewed. Then the experimental setup is described followed by results from the experiments and a discussion.

2 STATE OF THE ART

Nature has been a constant source of inspiration since the dawn of the technological age, but the systematic use of biological principles in engineering design, also referred to as biomimetic design, is a very young discipline. A number of researchers have worked with this problem and proposed different approaches to handle the biomimetic design work and how to represent the biological analogies.

Lindemann and colleagues describe a procedural model involving formulation of the intention, correlation with biological systems, analysis of the correlated systems and realisation of the technical solution (Helten et al. 2011, Stricker 2006, Lindemann & Gramann 2004 Gramann 2004). The correlation with biological systems is proposed done using a transfer checklist between technical functions and terms in biology. The checklist facilitates transfer on a high abstraction level using textual rather than graphical representation, and is limited to the biological analogies that are indexed in the system.

Shu and colleagues highlight the problems in natural language processing which include the engineering-biology terminology differences. They access the biological knowledge by using standard textbooks (Shu 2006). Finding biologically meaningful keywords that corresponds to engineering keywords is not straightforward (Cheong et al. 2008). The proposed solution is to find keywords in the functional basis (Stone & Wood 2000) and use WordNet (wordnet 2010) to generate synonyms. The functional terms are translated into biological equivalents by identifying nouns and so-called bridge-verbs often used close to the functional keywords in a biological text (Cheong et al. 2008). The approach makes possible to access a large number of biological analogies, but due to the biological terminology the risk of fixation is large. Mak and Shu present a case study where students produced concepts using strategically similar analogies when they were given biological descriptions where underlying principles were apparent (Mak & Shu 2004). This was in contrast to concepts made from biological information where the principles were not explained. In other words the presence of abstract functional principles was important for the analogical reasoning.

Charkrabarti and colleagues have developed the so-called SAPPhIRE model of causality that supports the ideation process and the IDEA-INSPIRE tool that provide analogical ideas of natural and artificial systems (Sarkar et al. 2008). The SAPPhIRE model defines 7 basic attributes (called constructs) that are used to describe functionality, behaviour and structure for both artificial and natural systems. The IDEA-INSPIRE tool includes a database with more than 700 entries of natural and artificial phenomena that can be searched using the 7 attributes. Sartori and colleagues analysed the transfer of biological knowledge by studying twenty industrial cases of biologically inspired product development from literature, and found that most transfers in these cases took place at lower levels of abstraction (Sartori et al. 2010). They also demonstrated that providing SAPPhIRE model-based descriptions and guidelines (as opposed to natural language descriptions and generic guidelines) for transfer of biological analogies better support transfer of biological stimuli to technical designs while encouraging ideation at higher levels of abstraction. Use of SAPPhIRE-based guidelines resulted in a shift in biomimetic transfer from largely part and organ (i.e. lower) levels to organ and state change (i.e. higher) levels of abstraction.

Vincent et al. (2006) developed a database of biological effects using TRIZ methods of contradiction analysis. The TRIZ-method helps the designer to analyse the functional problem and to configure the search for biological analogies. The more formal functional analysis helps the designer to be focused and limits fixation, but require that the designer is willing to invest in leaning the method.

Design fixation is the blind adherence to a set of ideas or concepts limiting the output of conceptual design. Jansson and Smith described experiments that showed how design students became fixated when problem assignments were made concrete with examples (Jansson & Smith 1991). Their experiments showed how one group of students had an overweight of design features found in the solution example compared to the control group that was not given any solution example.

Helms et al describes how students become fixated when searching for biological analogies (Helms et al. 2009). The students had a tendency of fixating on the first found biological analogy and following reject other analogies without proper reasoning. In our opinion it is possible that a more formal functional description of found analogies like biocards would have forced students to a better discussion and choice of analogy.

Asknature is an online biological database targeted towards people working with biomimetics (Asknature 2014). By specifying a functional problem Asknature's search function will display a number of relevant biological phenomena that solve similar functional problems. Each phenomenon is typically displayed as a picture of the biological organism and a short text describing how it solves the problem. The descriptions reminds of the concrete biocards described in this paper, even though they are not as standardised since they are made by different authors with knowledge about the organism.

3   METHODS – THE EXPERIMENTAL SETUP

Two identical experiments were carried out in India and Denmark. In both cases the test subjects were students from a master level product development course. All had at least 3 years of university studies behind them and they were all experienced in design and product development work. The students expected to be introduced to bio-inspired design through working with exercises. The experiments were done in groups of 3-7 persons following the procedure shown in Table 1. Students were asked to propose solutions to a predefined engineering problem. They were asked to first analyse the problem by visualising it with hand drawings (Figure 2). Then they formulated search keywords and conducted a brainstorm identifying about 10 biological organisms for the posed problem for each group. In this way they identified potential analogies (far domain) that could be used. Each group were then asked to select 2 biological organisms and create 2 types of biocards for each: One describing the functionality of the organism in concrete terms close to the biological domain and another describing the functionality in abstract terms close to a technical domain. Each group therefore produced 4 biocards for 2 biological organisms. The cards were collected and the groups were asked to make a traditional brainstorm to propose conceptual ideas for design solutions. To avoid bias from the functional problem they had worked with so far they were given the other design problem (Table 2), of which they had not heard of before this point. The conceptual ideas were documented on paper with drawings and short explanation statements. This was followed with a bio-inspired session where the groups were given biocards made by two other groups and again asked to propose conceptual ideas for design

solutions – but this time with inspiration from the biocards they were given. Half of the groups were given concrete biocards and the other half abstract biocards. All students filled out questionnaires individually hereafter.

Table 1. Overview of activities in experiment

|	Introduction + division into teams
Task 1	Each member in each team draws a description of the problem
Task 2	Search terms are formulated within each team and about 10 biological analogies are proposed using brainstorm.
Task 3	Two analogies are selected and described on two different type of bio-cards: Concrete and abstract biocards
Task 4	Each group is given a new design problem and asked to brainstorm and sketch conceptual solutions
Task 5	Each group is given either abstract or concrete biocards and asked to sketch conceptual solutions
	Fill out questionnaire
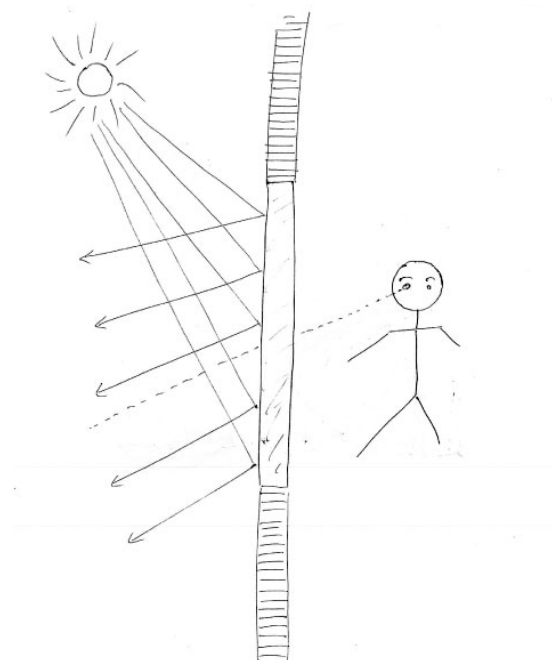
Figure 2. Problem analysis made by workshop participants for problem A by visualizing the problem using hand drawing.

Two design problems were prepared beforehand:
Problem A: Windows that shade for the sun but allow a view.
Problem B: Reduced consequence of collision

Table 2. Overview of assignment and type of biocard for each group

Concrete card in task 5	From group	Abstract card in task 5	From group
Group 1	3 and 4 (probl. B)	Gr. 2	3 and 4 (probl. B)
Group 3	1 and 2 (probl. A)	Gr. 4	1 and 2 (probl. A)

In the questionnaire students were asked to rank each of their conceptual solutions on a scale from 1 to 5, 1 being not novel and 5 being as novel as the most novel thing they have ever heard of. The novelty of the conceptual design solutions was evaluated by using the ratings by participants as seen in the questionnaires.

Mean values and standard deviations were calculated for the novelty of solutions generated from traditional brainstorm, from concrete biocards and from abstract biocards. The null hypothesis was that answers for concrete and abstract biocards belonged to the same greater dataset and had the same mean. This was tested using a student T-test assuming the worst case where the two data sets had unequal variance (heteroscedastic). The T-test determines the probability of whether the means of the two datasets are equal. If the probability is low, e.g. lower that 5%, it is unlikely that the two means are equal, or said in other words, it is likely that the two means are different. In our case the T-test is used to determine if questionnaire means of answers on the novelty of solutions found from either abstract or concrete biocards are different. The T-test is a parametric test that requires datasets to be normally distributed. Since the data are not normally distributed the data was also analysed using the non-parametric Wilcoxon's test. The tests showed the same tendencies, and results for both type of tests are shown here. The statistics was calculated using the functions in Microsoft Excel (MS Excel 2010) and cross checked using the open source statistical software R from the Cran project (cran-project 2014).

4   RESULTS

24 students participated in the Danish study and 15 in the Indian study giving a total of 39 respondents across the studies. Together they produced 61 conceptual solutions using traditional brainstorm and 44 conceptual solutions using biocards. The groups working with concrete biocards made 25 conceptual solutions while groups working with abstract biocards produced 19 conceptual solutions.

Table 3. Number of concepts & novelty values found from questionnaires and t-test / Wilcoxon-test probabilities

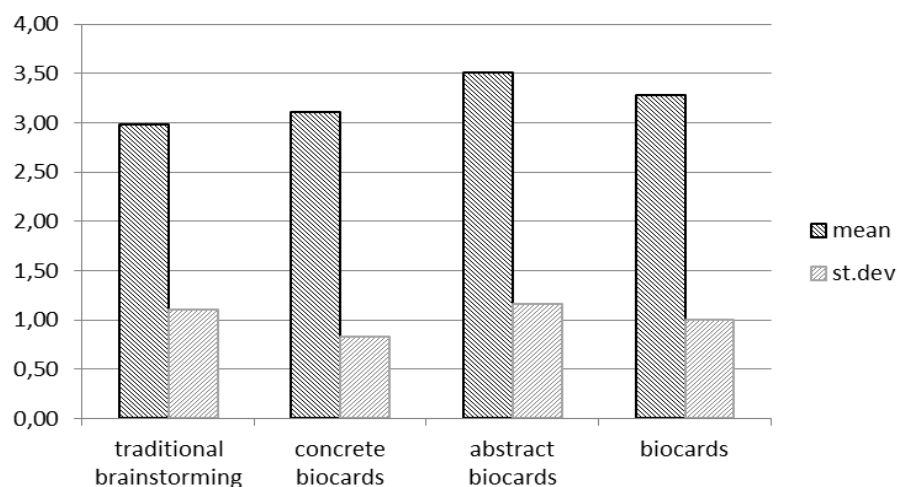|	# of concepts n_i / mean # pr group	# of ratings	average novelty x_i	st.dev. novelty σ_i	$P(n_i=n_j)$	$P(\text{mean } x_i = \text{mean } x_j)$
t: traditional brainstorming	61 / 7,6	264	2,98	1,11		
c: concrete biocards	25 / 6,3	120	3,11	0,83		
a: abstract biocards	19 / 4,8	86	3,51	1,16		
b: biocards (concrete + abstract)	44 / 5,5	206	3,28	1		
trad.brainst(i=t)=biocards(j=b)					4,8% / 4,3%	0,2% / 0,3%
concrete(i=c)=abstract(j=a)					34,7% / 64,4%	0,6% / 0,1%

Figure 3. Mean novelty values found from questionnaires for concepts generated by traditional brainstorming, concrete biocards, abstract biocards and all biocards (concrete + abstract).

Concepts generated from biocards score a mean of 3,28 on a 1 to 5 scale for novelty in the students own evaluation shown in Table 3 and Figure 3. In comparison concepts generated from traditional brainstorming scored a mean of 2,98. Concepts generated from abstract biocards got 3,51 while concepts from concrete biocards got 3,11. Statistical tests confirm that both the differences are significant with significance levels greater than 1%. Traditional brainstorming produced 61 concepts compared to 44 concepts generated using biocards. Statistical tests also here confirm that the difference in mean number of concepts is significant with significance levels greater than 5%. Abstract biocards produced 19 concepts while concrete biocards gave 25 concepts, but the statistical tests show a high probality for the null hypothesis, i.e. the means of concepts are not significantly different.

Table 4. Number of concepts & novelty values found from questionnaires from Danish experiment and t-test / Wilcoxon-test probabilities

	# of concepts n_i / mean # pr group	# of ratings	average novelty x_i	st.dev. novelty σ_i	$P(n_i=n_j)$	$P(\text{mean } x_i = \text{mean } x_j)$
t: traditional brainstorming	27 / 6,8	156	2,69	1,10		
c: concrete biocards	12 / 6	79	3,06	1,00		
a: abstract biocards	9 / 4,5	49	3,22	0,84		
b:biocards (concrete + abstract)	21 / 5,3	128	3,13	1,23		
trad.brainst(i=t)=biocards(j=b)					34,4% / 24%	0,1% / 0,1%
concrete(i=c)=abstract(j=a)					58,8% / 100%	42% / 37,6%

Table 5. Number of concepts & novelty values found from questionnaires from Indian experiment and t-test / Wilcoxon-test probabilities

	# of concepts n_i / mean # pr group	# of ratings	average novelty x_i	st.dev. novelty σ_i	$P(n_i=n_j)$	$P(\text{mean } x_i = \text{mean } x_j)$
t: traditional brainstorming	34 / 8,5	108	3,39	0,98		
c: concrete biocards	13 / 6,5	41	3,20	0,81		
a: abstract biocards	10 / 5	37	3,89	0,94		
b: biocards (concrete + abstract)	23 / 5,8	78	3,53	0,94		
trad.brainst(i=t)=biocards(j=b)					10,1% / 14,4%	33,7% / 39,2%
concrete(i=c)=abstract(j=a)					65,7% / 100%	0,08% / 0,02%

In Table 4+5 the equivalent results are shown for the Danish and the Indian part of the experiment separately. Also here we see differences in novelty evaluations in favour of biocards vs traditional brainstorming. Similarly abstract biocards score higher mean values for novelty than concrete biocards. However the statistical tests could only show significance for two of the results, probably because of the smaller sample sizes. Fewer concepts were generated when using biocards compared to traditional brainstorming and when using abstract biocards compared to concrete biocards, but statistical tests did not show significance – again most likely because of smaller sample sizes.

5 DISCUSSION

In two experiments with Indian and Danish students we have investigated the effect of abstraction level in biocard descriptions on the novelty of proposed new solutions using bio-inspired design. The

experiment also explored whether concepts generated using biocards where more novel than concepts generated using traditional brainstorming. The novelty has been evaluated based on the students own opinion as expressed in answers on questionnaires.
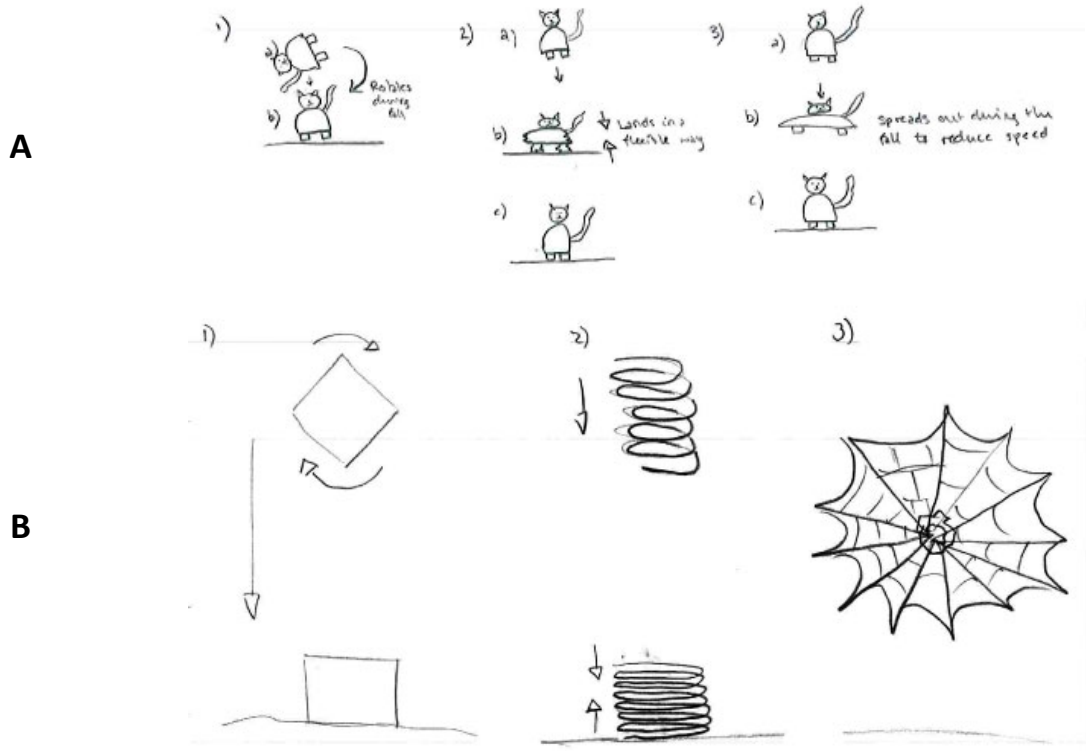

Figure 4. Two examples of the graphics in (A) a concrete biocard and (B) an abstract biocard, both for the biological phenomena: 'The landing cat'
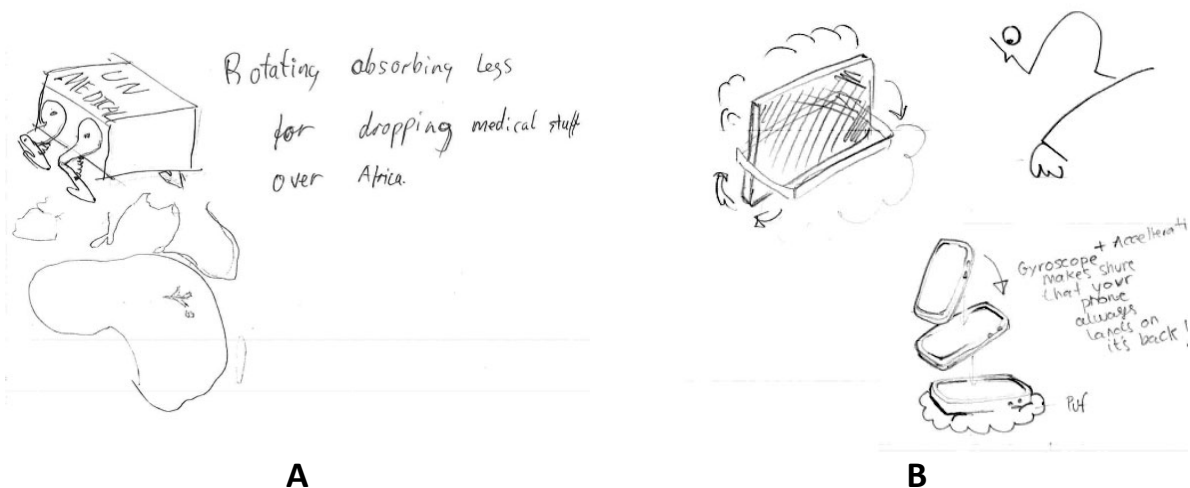
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Figure 5. Two conceptual solutions for a collision protection mechanism inspired by the landing cat. (A) is inspired by the concrete biocard and (B) is inspired by the abstract biocard in Figure 4.

The question of which method produces the most novel design results was earlier explored by Keshwani and colleagues using the SAPPhIRE model of causality to evaluate on which abstraction level a concept was different from known products (Keshwani et al 2013). They found a significant difference on the novelty for concepts generated using biocards compared to traditional brainstorming. In the present study the novelty of concepts was evaluated using the opinion of the participating designers as expressed in a questionnaire they filled out after the experiment. This study confirms that

conceptual solutions made with inspiration from biocards scores higher on novelty compared to concepts generated from traditional brainstorm. The mean value of novelty scores for traditional brainstorm was 2,98 on a 1-5 scale, i.e. just below middle. The equivalent mean novelty score for solutions made from biocards was 3,28 which is 0,3 higher. Statistical tests showed that it is significantly unlikely that the two mean values are identical. When using biocards the participants produced significantly fewer concepts, which could be expected, since it takes time to read and understand the biocards. Another reason could be that participants being engineers found it difficult to apply inspiration from the biological domain. However the good evaluations of the biocard method could be questioned since the participants could be biased. The experiment was part of course where the students knew that the instructors were positive about bio-inspired design, so without being aware of it they might have rated biocards higher.

However the main question in the present study was if abstract biocards performed better than concrete biocards. Here it should not be expected that participants were biased in favour of the one or other type of biocards. All participants produced both type of cards and they did not know if the instructor preferred one in favour of the other. When generating conceptual solutions to the design problem each group was only given either concrete or abstract cards. The answers on the questionnaires showed significantly higher mean novelty values in favour of abstract biocards indicating that solutions on average were more novel according to the participants. This result confirms the findings by Srinivasan & Chakrabarti (2010) that ideation at higher levels of abstraction leads to greater novelty.

In some cases the conceptual solutions were very close to the biological inspiration and could be classified as direct transfer of biological knowledge rather than inspiration from abstracted principles. An example was the concrete biocard (the graphics are shown in Figure 4A) describing how cats avoid getting hurt when falling. A proposed solution is shown in Figure 5A where the protecting mechanism on a box to be dropped from an airplane is shaped as cat legs with springs. The students seem to be fixated on the biological organism. In contrast another student group working with the abstract biocard in Figure 4B proposed a protecting mechanism for smartphones shown in Figure 5B where a build-in gyroscope would assure that the phone will land on its back. The analogy to the rotating mechanism is found at a higher abstraction level.

A possible weak element of the experiment is the used biocards. Abstract and concrete biocards were made by the students and given to another group by the instructors for the generation of solutions. There is a risk that the abstraction and detailing level could be different on the various biocards. It is not the impression of the authors that this is the case, but to rule out this doubt a slightly different experimental setup can be proposed for a future experiment. Instead of using biocards made by the participants in the experiment premade biocards could be used as datum. All groups would then have identical starting points.

6 CONCLUSION

Biocards are formal descriptions of biological phenomena and their underlying functional principles. They are used in bioinspired design to document search results and to communicate the findings for use in the further design process. The present study explored the effect of abstraction level used in biocards. This was done in two workshops conducted with design students in Denmark and India. Students were given a design assignment and instructions for how to perform the BID ideation work. Half of the students were given biocards with abstract descriptions while the other half got biocards with concrete descriptions. The students evaluated the novelty of found solutions. They rated novelty of each solution on a scale from 1 to 5. Mean values for abstract descriptions were 0,3 higher than for concrete descriptions indicating that more innovative solutions were found when students used biocards with abstract descriptions compared to concrete descriptions. The difference in mean value is significant with a confidence level better than 1%. It seems likely that more abstract descriptions in biocards helps avoiding design fixation in biomimetic design work.

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