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NATURALLY ORIGINAL: STIMULATING CREATIVE DESIGN THROUGH BIOLOGICAL ANALOGIES AND RANDOM IMAGES

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1. Introduction

Engineering design is frequently described as an ill-defined problem: usually many possible solutions exist and there are no clearly defined rules to obtain these solutions [Goldschmidt 1997], [Cross 2003]. The process of generating design solutions is both a divergent and convergent process with a variety of solutions being created and few being selected for further development. A number of methods exist to support the divergent process (e.g. brainstorming methods. 6-3-5 method) and other to support the convergent process (for example ([Pugh 1997]). Bioinspired design is one such method that has been proposed to support creativity, where distant analogies are used to support the creative process. This paper focuses upon understanding the effects of using stimuli from biology as compared to other creative methods.

1.1 Analogies

Inspiration for design concepts can come from a variety of sources, for example, the use of analogies have often been observed during conceptual design. Using analogies involves accessing and transferring elements from familiar categories (often referred to as the 'source') to use it in constructing a novel idea ('target') in an attempt to solve a problem or explain a concept, these sources can be other products or nature [Gentner 1983]. In analogical transfer, the 'distance' between the source and the target (the application of the analogy) may be large or small. For example, a designer developing a new aircraft jet-engine may make an analogy to other aircraft jet-engines (referred to as within-domain or local analogies) or make an analogy to human anatomy or radios in developing the design (referred to as between-domain or distant analogies).

Within domain analogies involve greater superficial similarity between the source and target compared to lesser amounts of superficial similarity in distant analogies. This increase in superficial similarity may make local analogies easier to access (e.g. [Genter 1993], [Ball and Christensen 2007]). Both close and distant analogies involve structural similarity. Distant analogies (between domain) involve two vastly different bodies of knowledge, e.g. biology to medical products and it may be more difficult to ensure successful transfer of solution elements in design problem solving from the source to target as the domains may differ in multiple subtle ways [Gentner 1993].

The domain in which analogies are used may affect their distance, for example, Dunbar [1995, 2001] found that in real-world studies of expert scientists within the domain of microbiology, distant analogies were very rare in comparison to local and regional analogies (i.e. within domain).

Empirical studies investigating the use of analogies within the design field show that within domain analogies and far domain analogies vary in their usage dependant on the design problem and the industry. In the aerospace industry predominantly analogies from the aerospace industry (i.e. within domain) were observed [Ahmed and Christensen 2009] whereas in studies of toy designs predominantly between domains analogies were observed [Ball and Christensen 2009]. In design, Casakin [2004] found that in an experimental study of visual analogy both novices and experts produced more between-domain than within-domain analogies.

Studies from the design field indicate that between domain analogizing is frequently used, however the design domain and design task in question may in part determine the appropriateness of using within or between domain analogies. The more radical innovation type task [Ball and Christensen 2009], thus produced more between domain analogies than in less innovative domains, e.g. variant design tasks such as in the aerospace industry [Ahmed and Christensen 2009].

1.2 Fixation and analogical distance

The effect of fixation (being limited and biased in one solution) maybe a concern with analogies. Research on fixation and exemplar influence in generative tasks supports the notion that having or making examples available will bias people's creations toward features in those examples. A number of studies have shown how providing [Jansson 1991], [Ward 1994], [Marsh 1999], [Dahl 2001], [Jaarsveld 2005] or retrieving [Ward 1994] existing examples may inhibit generative creative processes. Examples in this sense lead to a higher proportion of property transfers from the examples into the subject's own work [Marsh 1996] and notably given objects from similar domains share more superficial similarity than objects from dissimilar domains. Since superficial similarity is one of the key driving forces of analogical access, this lead to the expectation that the presence or availability of within-domain exemplars increases the likelihood of within-domain analogizing [Marsh 1996]. In other words, the presence of within-domain examples may make it difficult for creative problem solvers to break away from local analogies, since superficial similarity dominates access, and distant analogies are less superficially similar than local analogies. Therefore providing designers with prior within-domain examples result in a bias toward creating features contained in those examples [Linsey 2007]. This was supported by Christensen and Schunn's [2009] study of engineering designers illustrating that the prevalence of between domain analogies in design conversations are reduced when referencing prototypes as opposed to design conversation that is unsupported by such prototypes. The result suggests that if exemplars are present, the designers are less likely to think about other domains than the present one. Lindsey et al.'s [2007] study with design students found that the representation of analogies also influences originality. Analogies presented more generally facilitated the use of the analogy in novel solutions. Furthermore, the proportion of between domain analogies used was a strong indicator of the originality of the resulting design. Apparently, the presence of one or more within-domain exemplars hindered students in producing original responses.

2. Research Aims

From the literature, research into developing tools for biomimetic (bioinspired) design was evidence with an large number of efforts to use biology to support conceptual design (e.g. [Cheong 2008], [Sarkar 2008], [Lenau 2010], [Lenau 2011]) and also a number of studies to investigate the use of analogies within creativity were reviewed. The studies point to the fact that variant design domain are more likely to use analogies that are closer to the source and more original design problems are likely to use more between domain analogies. However the studies do not show the expected benefit from using analogies from nature over other types of creative stimuli. Bio-inspired design is an area of interest to a number of researchers working within creativity (e.g. [Vincent 2003], [Cheong 2012], [Goel 2012]). Similarly, little is known about the effects of using stimuli from biology as opposed to other stimuli on the creative process and on the solutions produced. Hence this paper focuses upon the effect of using biological analogies versus random images during facilitated brainstorming sessions, using industrial problems.

The research is primarily interested in the benefit of using inspiration from biology for supporting engineering design, hence the effect of using biological analogies was investigated and rather than comparing this to no stimuli, random images were used as a control. The aim of the research was to investigate the effect of using biological stimuli and random stimuli on the originality and usefulness of solutions. For this research these were defined as:

- Originality: in relation to past solutions (within the company and on the market)
- Level of usefulness: the potential value of the solution

In addition to these aims, the secondary aim of assessing the process of using these two different stimuli was also of interest

3. Method

Two experiments were conducted with six participants from industry. The participants were from four different companies, and were asked in advance to send a problem description of an ongoing problem within the company. The problems were selected by companies represented problems with a potential to improve the market value of their products. Two problems statements were used for the experiment. The problem statements consisted of a short description of the problem, a couple of lines describing the context plus a few functions described as noun and verbs. The problem statements are shown below. The functions for each statement were used to search for analogies from biology from the Asknature website. The website utilizes a taxonomy that can be used for searching, and this was used with the function terms.

As more analogies were found that were feasible to be employed during the duration of the experiment, a random number generator was used to select the analogies so that 5 analogies were found for each function term for the two problems (see Table 3). For each of the biological analogies, a 'biocard' was produced which was adapted from the asknature website, with redundant information (references, list of experts, etc.) removed and the functions, as described in the problem statement, was clearly stated the top of each card, e.g. store liquid, to facilitate the selection of the cards during the brainstorming activity.

Table 1. Experiment with team problem and method

Team	Problem	Session 1	Session 2
Team 1	Colour changing materials	Biological cards	Random images
Team 2	Handle liquid within a limited space	Random images	Biological cards

The participants worked in two teams of three and were asked to generate solutions for one of the two problems for a total of thirty minutes. To control the effect of the experience of the team, the problem owners were placed in the team in which their problem was being solved. In addition, the same team worked on the same problem with both methods, while the order that the teams received the methods was reversed to take into consideration any learning effect (see Table 1). The participants experience and background is summarized in Table 2.

Table 2. Background of participants

Team	Participant	Level of Experience
Team 1 Colour Changing Material	1	Problem Owner 20+ years Headset Design
	2	4 years Engineering Design
	3	2 years Medical Instrument Design
Team 2 Handle Liquid	4	Problem Owner (2 years) Medical Devices
	5	1 year Headsets design
	6	Four years Architect Consultancy

The problem owners presented the problem prior to the brainstorming sessions, and showed examples of the products. The teams were also supplied with written instructions. The teams worked on the same problem, e.g. controlling liquid for an ostomy pouch, for two sessions of thirty minutes. For each session the teams were given either the random images or the biological cards. The teams were instructed to pick up the cards as they wished individually. The order of working with the biological cards and random images was switched for the two teams, to counteract for tiredness and learning effect, after working on the same problem. The teams brainstormed aloud and adapted each other's solutions. However the solutions were sketched individually. All sessions were video recorded, and solutions were collected on individual sheets and colour codes were applied enabling the tracing of the individual authors of the idea. For the presented research, the video recordings were only used to establish idea generation time points.

Table 3. Problems described with function terms

Technical Problem:	*Color changing materials*	*Handle/control liquid output within a limited space*
Main issue and context	Design of headset. To reduce stigma and investigate colour changing materials to make headphones discreet.	Reduce leakage and hence insecurity in Ostomy pouch where human waste (e.g. urine or liquid stool) is stored.
Functions (search words)	Color changes with color of environment	Control Liquid
	Dirt resistant surface	Change Consistency
	Color adaptation	Handle Volume

For the random pictures method, initially 1000 pictures were chosen randomly from picture sites on the Internet (such as Shutterstock, for more details on the pictures, see [Christensen 2010]). All pictures were in high resolution. From this initial sample of images, only images containing focal objects or persons were selected (effectively removing images of abstract art or images where the content could not be discerned). From this restricted sample, all pictures that contained nature were removed to ensure that no information from the biocards could be duplicated. The random images depicted photos of people, products, contexts and situations, for example bubbles or a toilet. The images were selected using random number generators where repeated images (if the same random number was generated) were also removed, 5 images were randomly selected for each function (see Table 4 and Table 5) to ensure that the same number of random cards was available as the number of the biocards during the brainstorming sessions. Two non-overlapping sets of 20 and 15 images were used for the two experimental groups respectively, the number of random images matched the number of biocards for each problem.

Table 4. Corresponding analogy for functions and sub-functions for the controlling liquid problem

Function	*Taxonomy*	*Corresponding analogy*
Control liquid	Capture, absorb, filter liquid	Brown dog tick, Barking spider, Welwitschia, Bromeliads, Tree frog
	Distribute liquid	Plants (vascular systems), Plants (xylem), Oaks, Phalarope, Plants (vein system)
	Avoid loss of liquid	Human (skin), Lungfish, Quiver tree, Pebble plant, Umbrella thorn trees
	Modify size, shape, mass,volume	Pine (cone scales), Worms (skin aids movement), Sea anemone, Hawk moth, Resurrection fern

Table 5. Corresponding analogy for functions and sub-functions for the changing colour problem

Function	*Taxonomy*	*Corresponding analogy*
Change (& adapt) colour	Modify state/ light. colour (Generate	Morpho butterfly, Ray-finned fish, Giant wasp, True wasp, Marble berry

	colour & adapt colour)	
Discrete appearance & Adapt colour	Protect from biotic factors > Animals (camouflage)	Cuttlefish, Lionfish, Caddisflies, Pebble plants, Earthworm
Dirt resistant	Prevent from dirt. solid	Common earthworm, Morpho butterfly, Sacred lotus, African mole-rat, Tokay gecko

3.1 Hypothesis

Prior to the experiment it was hypothesized that:

H1: More solutions would be produced using the random images than the biocards

Measure: the number of solutions produced in the two thirty minutes sessions using the random images and using the brainstorming. In addition the participants evaluation of the influence of the biocards on the originality of the solutions they produced.

As the biocards contained much more information, they were an A4 page with text and photos and were prepared in advance to match the functions described in the problem statement, these were expected to require a greater time to process in comparison to the random images. In addition, as these are examples of between domain analogies, these were expected to require more time to understand and then transfer to the context of the engineering problem.

H2: Brainstorming with the Bio-cards would produce more original ideas than with the random images.

Measure: originality scores applied by the problem owners and comparison of participants' evaluation

Previous research in the use of analogies shows that the distance (how far removed the analogies are from the context they are applied to) is related to originality, in that variant design domains tend to use more within domain analogies and more original design domains use more between domain analogies. Hence it was hypothesized that distant analogies were more likely to produce highly original solutions then close analogies (within domains). Since the biocards are from nature they are examples of between domain analogical sources and therefore were expected to produce original solutions when compared to random images which only in some cases are expected to lead to original solutions

H3: Brainstorming with the biocards was expected to produce more useful ideas.

Measure: the usefulness scores applied by the problem-owners and comparison with the participants' evaluation of the influence of the biocards on the usefulness of the solutions they produced.

As the biocards were produced in advance to match the function of the problem descriptions they were expected to (due to the pre-selection of the input ensuring relevant information) lead to more useful solutions than with the random images. In addition the information in the biocards described a phenomena observed in nature carrying out the same function as in the design problem, whereas the random images did not describe any principles/solutions but were simply images.

3.2 Evaluation of solutions and Process

Evaluation of solutions: As the problem owners were considered the experts of the problem domain (medical device and headset designs) they were asked to evaluate the solutions (including their own) with respect to originality and usefulness. The problem owners were present during the brainstorming and contributed to the solutions, however they had not been exposed to the images or biocards before the brainstorming session. A seven point scale was used where the product owners assessed the solutions that were produced in that session (see Table 6, a similar scale was used for usefulness). They were asked to assess the usefulness and originality of each solution as defined in section 2. While the evaluation method of asking problem owners to evaluate team ideas can said to be strong on external validity, it suffers from a lack of a measure of reliability given we were unable to obtain multiple expert ratings.

Table 6. Scales used for assessment of originality

Very unoriginal	Quite unoriginal	Slightly unoriginal	Neither unoriginal/ original	Slightly original	Quite Original	Very Original
-3	-2	-1	0	1	2	3

Evaluation of process: In addition to the assessment of the solutions by the problem owners, the process of using the biological and random images was also assessed. The participants were asked to rate (for both the random images and the biocards in turn):

- The number of solutions that were inspired by the cards (*results*)
- The effect of using the cards on the level of originality (*results*)
- The effect of using the cards on the level of usefulness (*results*)
- How easy it was to use the cards (*learning*)

These questions, as indicated above, combined with the assessment of the solutions covered the *learning* and r*esult* parts of the Kirkpatrick [1959] model to assess tools and methods. In addition comments were collected from the participants to cover the *reaction* to the methods*,* whereas change resulting in the designers *behaviour* (the last part of Kitkpatrick model) was not assessed.

4. Findings

It was hypothesized (H1) that as the biocards would require more processing time (due to the textual information) more solutions would be produced during the session using the random images than with the biocards. Looking across both teams, a total of 105 solutions were produced, 56 with the random images and 49 with the biocards (see Table 7). More ideas were produced in the 2nd half of the biocard session than the 1st half (59 %) when compared to random images (36 %) ($\chi^2(1) = 5.78$, $p < .02$) in support of the hypothesis, suggesting that the first part of the biocard session was mainly spent on comprehending the source analogs, i.e. understanding the biological analogies and how these could be transferred to the engineering design problem, thus limiting idea generation.

Table 7. Number of solutions produced with each stimuli

Team and problem	*Brainstorming Method*		
	Random Images	*Biocards*	*Both*
Team 1:Color changing materials	36	26	62
Team 2: Control liquid	20	23	43
Both teams:	56	49	105

Originality: From the second hypothesis (H2) it was expected that the solutions that were produced through using the biocards would be more original than those with the random cards.
The evaluation of the solutions showed that this was indeed the case with the mean of the solutions being 1.29 for originality (i.e. between slightly to quite original) as opposed to 0.03, i.e. just above (neither original/or unoriginal) the solutions produced using the random images (see Figure 1) ($t\,(103) = 3.48$, $p < .001$). Figure 1 shows that the originality of the solution increased with the biocards, and that this effect was true for both cases, but was very apparent in the team working with the colour change problem.
Usefulness. From the third hypothesis (H3) it was expected that the solutions that were produced through using the biocards would be more useful than those with the random cards. The evaluation of the solutions showed a slight decrease with the level of usefulness for solutions produced with the biocards (mean of 0.49) than those with the random cards (mean of 0.61), i.e. both of these were

between not useful/or useful to slightly useful in the evaluation scale (see Table 6). However, an independent t-test showed that these results were not significant ($t(103) = -0.38$, NS). Therefore this hypothesis was rejected.

Table 8. Originality and usefulness of solutions with random images and using biocards

	Approach	*No of concepts*	*Mean*	*Std. Deviation*
Originality	Biocards	49	1.2857	1.84
	Random	56	0.0357	1.84
Usefulness	Biocards	49	0.4898	1.65
	Random	56	0.6071	1.52

Evaluation of process: Each of the participants were asked to evaluate the process. They evaluated the influence of the biocards and random cards on the originality and the usefulness of the solutions they produced. The level of originality as assessed by the participants (as opposed to the assessment of the solutions by the problem owners) for their solutions produced using the biocards was assessed as the same as with random images (1.25. slightly to quite original) with both approaches. Hence the participants perceived both approaches as raising their originality of their own solutions, whereas the problem owners evaluated the solutions produced with the biocards as more original.

The participants evaluated the level of usefulness as being higher with the biocards (1.83, i.e. leaning towards quite useful) than in comparison with the random images (0.83 i.e. slightly useful) see Table 9. This was in contrast to the results as evaluated by the problem owners, where no significant differences were observed. One reason for this maybe the level of information supplied in the sketches (very few annotations and a quick sketch) see Figure 2, Figure 3, was not detailed enough for a thorough explanation of the solution and hence difficult to assess.

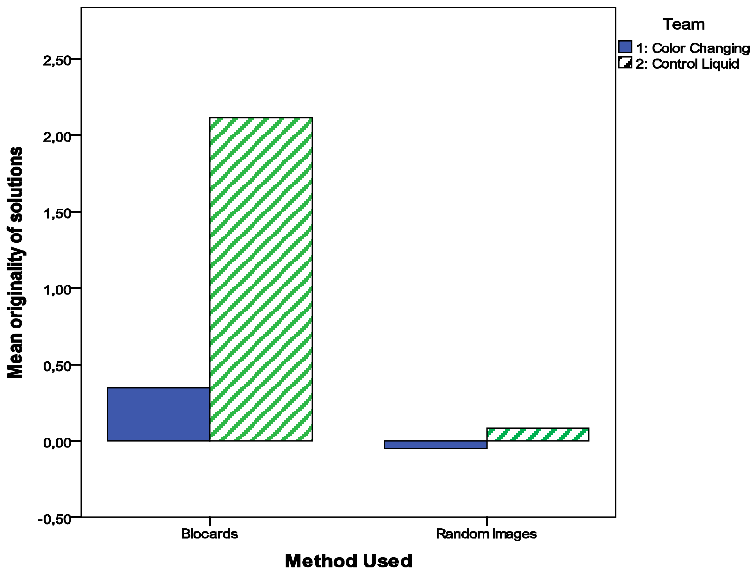

Figure 1. Originality for solutions created using random and biocards

Ease of using the approach: The participants also assessed how easy it was to learn the two approaches. The random images were assessed as very easy (mean of 2) as opposed to the biocards that were rated neither easy nor difficult to use (mean of -0.08, sig. (2.tailed 0.03), see Table 9. This indicates that the random images were much easier to use, which is somewhat to be expected as biocards are distant analogies hence require more effort to process and transfer to a new target analog, i.e. to the design problem.

Table 9. Assessment of process by participants

Measure	*Methods*	*Mean*	*Std. Deviation*
Usefulness	Biocards	1.83	.75
	Random	0.833	1.47
Originality	Biocards	1.25	1.41
	Random	1.25	.76
Learning	Biocards	0.0833	1.62
	Random	2.00	1.10

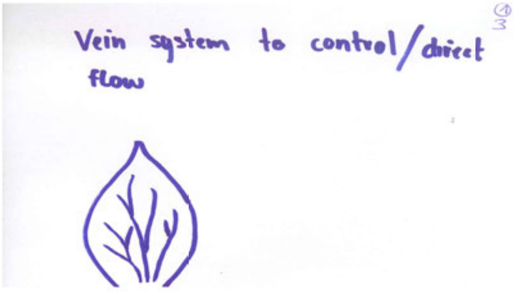

Figure 2. Example solution for control liquid (biocards)

Figure 3. Example solution for control liquid (random)

5. Conclusions

The aim of the research was to investigate the effect of using biological stimuli and random stimuli on originality and usefulness of solutions. An experiment with industry participants was conducted with two industry problems. The problem statements were used to create relevant biocards and a control with random images was used to understand the effect of both approaches on the originality and usefulness of the solutions produced. Counter to expectations the random images acted as much more than a control, and the participants used the images as inspirational associations prompting ideas, whilst the biocards were used more directly as analogies. These differences can assist in understanding when to apply these methods to facilitate creativity during the design process. The random images were able to activate a wide variety of associations that translate into amongst others, personas of possible uses of the products, and also situations where the product would be used. Whereas the biocards focused primarily on understanding the principles employed in nature and transferring these to the design problem. The biocards narrowed the possible solutions to the phenomena observed, and hence maybe more appropriate in brainstorming when the problem space is well mapped out, i.e. convergent phase, whereas the random images maybe more useful at earlier parts of the design process, where the needs and specification of the product need to be understood, i.e. during divergent thinking and task clarification. Many of the random images triggered the identification of user needs.

The experiment showed that it is possible to use distant analogies, i.e. biocards, to increase originality of the solutions. Although previous studies have shown this when compared to no method, this was also found to be true against another source of stimuli (the random images), this is an important finding to encourage research in bioinspired design. Although the two methods produced a similar number of ideas, they did so at distinct rates, where the biocards had fewer ideas initially, presumably due to analog source comprehension and alignment processes. In this interpretation, it should be noted that the experimental choice to use 5 biocard source analogs per session probably affected the idea production rate: more biocards would likely have further decreased idea production, as more time would have been spent comprehending and aligning the analogs to the current problem context. The participants' subjective evaluation of the methods showed that both random images and **biocards** increased the originality of the solutions, and the biocards were perceived as more useful. However, the biocards were also more difficult to use, this phenomenon is to be expected when translating knowledge from a vastly different domain (biology) to another (engineering domain) and hence requires researchers to focus efforts upon how to best to represent biological knowledge in order to better facilitate transfer to engineering design.

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