Bio-inspired design as a solution to generate creative and circular product concepts

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Abstract

Consumers are showing a growing concern for the environment and sustainability, while they keep their interest in more creative products that "delight" them and exceed their expectations. Consequently, designers must meet the circular economy (CE) requirements, but also provide creative solutions. The present research describes an experiment in which a group of designers were asked to solve design problems using two different methods: random stimuli and biomimicry. The results help to answer the question regarding whether methods focused on requirements (biological requirements in this case) are as effective for obtaining creative solutions as methods oriented towards creative ideas (specifically random stimuli). The paper also examines whether biomimicry stimuli promote circularity to a sufficiently greater extent than a random stimulus to compensate for the possible loss of creativity with respect to the random method. The results show that biomimicry stimuli promote circularity in the concepts without diminishing their creativity.

Keywords: biologically inspired design; collaborative creativity; concept generation; creativity process

1. Introduction

Consumers are showing a growing concern for the environment and sustainability. Because consumers also have the power to choose which products to purchase, companies find themselves under pressure to become more sustainable (Mota et al., 2015). This product sustainability can be defined as the satisfaction of the needs of human society without compromising the resources provided by the different ecosystems (Morelli, 2011).

Since the 1990s, companies have sought to reduce the environmental impacts caused by products throughout their life cycle by integrating environmental considerations into product design (De Pauw et al., 2014), (Stevels, 2009), which has led to ecodesign or design for environment (DfE). Ecodesign observes the key sustainable requirements in order to incorporate environmental factors into product design and development in the most efficient and appropriate manner (Tukker et al., 2001). For Tischner et al. (2000), ecodesign implies the development of products with environmental awareness, within the concept of sustainable design.

Furthermore, consumers are also looking for more creative products that “delight” them and exceed their expectations rather than just fulfilling the functional aspects (Elizondo et al., 2010; Horn & Salvendy, 2006; Saunders et al., 2009). At the same time, customers tend to prefer more circular products if they are compared with others that present identical attributes (Boyer et al., 2021). Also, the willingness to purchase the products increases if they are signaling as a green product (Khan & Kirmani, 2015).

Creativity therefore endows products with added value, and creative products have a positive impact on society, as well as having greater potential for market success. Nonetheless, creativity does not ignore the useful side, since most of the metrics that measure creativity in products combine novelty and utility (Besemer & O’Quin, 1989;

Chulvi et al., 2012; Kudrowitz & Wallace, 2013; López-Forniés et al., 2017a; Moss, 1966; Prabir Sarkar & Chakrabarti, 2011). Creativity could be said to be the response to a problem in a way that is both novel and appropriate, as well as useful and correct (Amabile, 1983).

Many authors define creativity as the combination of two factors to meet the design objectives, one relating to the novelty of the idea and the other to the appropriateness of the idea (Chulvi et al., 2012), (Shah et al., 2003), (P Sarkar & Chakrabarti, 2008). Novelty is one of the elements that characterize creativity in a product, and it is defined by the difference in its features compared to those of other existing products of the same type (Prabir Sarkar & Chakrabarti, 2011).

In addition, there is the appropriateness of the solution, which usually refers to utility, but may also involve other aspects and new features such as, for example, circularity. The fulfillment of the demands that need to be met by the product for the design to be complete and have all the necessary functions, in addition to the specific requirements of the problem it is solving, determines the appropriateness of the product, according to its degree of fulfillment. In these terms, Charter (2018) stated that designing for the circular economy requires thinking about how to introduce the features that will provide the product with circularity early in the creative design phases. Thus, since the demands of circularity become design requirements in order to introduce the circular economy model into the design of a product, their fulfillment determines, in this case, the appropriateness of the result, playing a very important role in defining the creativity of the product together with the novelty of the product and in defining the product itself. Creativity is usually defined in the literature as novelty and appropriateness, so this work is set in the definition of creativity as the combination of novelty and circularity,

circularity being the appropriateness (Ruiz-Pastor et al., 2022), (Sternberg & Lubart, 1999).

Designers must somehow meet the requirements of a design problem. They not only have to solve the useful aspects, but also provide novel ideas in order to achieve creative solutions. These initial requirements and limitations are what the designer has during the conceptual phase to understand the problem and the possible design space to be explored during the ideation phase. If the requirements are too open, the design task becomes hard in terms of knowing whether progress is being made in an acceptable direction and whether the task has been completed in an acceptable manner (Yamamoto & Nakakoji, 2005). In the same vein, Cucuzzella (2016) claimed that when the requirements are so open, it is too challenging to reimagine a different future, and consequently creativity is affected. Nevertheless, Cucuzzella (2016) also pointed out that creativity decreases when designers are expected to implement very strict design requirements, which means that the requirements are not open at all, and they must be fulfilled rigorously.

From all the foregoing, a first topic arises regarding whether circularity could be considered a “strict design requirement”. Assuming this to be a fact, the search for circularity could affect the creativity of the results, which is an undesired outcome (Ruiz-Pastor et al., 2021). Designers must propose concepts that satisfy both customer and engineering requirements (Oman et al., 2013) and, in this case, people want to meet the requirement of circular products, which also need to be creative. Moreover, several authors have claimed that sustainable design needs creativity (D’Orville, 2019; Kajzer Mitchell & Walinga, 2017; Lozano, 2014). Helping designers in this kind of task has been the motivation behind the creation of many design methods.

Over time, numerous design methods have been developed. These proposals could be differentiated according to their focus, as follows:

- Methods focused on providing solutions in one specific field, while there are others more oriented toward providing creative results, even if they are less concerned with helping to solve the specific requirements. Examples of methods focused only on solving a particular kind of problem are Kansei engineering (Nagamachi, 1995) for emotional design, the Taguchi method (Roy, 2010) and FMEA (Stamatis, 2003) as methods seeking to improve reliability, and biomimicry (Cohen & Reich, 2016), (Liu et al., 2019), which we can consider as being oriented toward improving sustainability and eco-efficiency (Gamage & Hyde, 2012).
- Creative-oriented methods, oriented towards providing large numbers of random ideas, like brainstorming (Osborne, 1957), SCAMPER (Eberle, 1996) or random stimuli (DeBono, 1970), and also others more focused on solving specific problems in a creative way, like TRIZ (Altshuller, 1984) or storyboarding (VanGundy, 1988).

By categorizing them into these two groups, it could be hypothesized that the methods focused on requirements (in the case of this work biological stimuli) will produce worse results in terms of creativity. This assumption could be in line with the study by (Chulvi et al., 2013), where it was seen that the more divergent type of methods, such as Brainstorming, provided more novel results.

In this same vein, there are studies that defend that the biological stimuli could cause fixation in designers (Helms et al., 2009). On the other hand, there is also research defending the idea that biologically-inspired design techniques have potential to make designers think out-of-the-box (Brezet & van Hemel, 1997), and design for systems innovation transforms systems in order to make design and innovation teams achieve new visions (Ceschin & Gaziulusoy, 2016). Since these statements seem to be opposites, the present work aims to provide a new approach to this topic by integrating the biological stimulus in a creative design method oriented toward the production of a large number of ideas. For this reason, the present research describes a practical experiment in which a group of MSc design students were asked to solve two different problems individually using two different methods. The use of random stimuli was selected as a creative method, and a biomimicry tool was chosen as the method oriented toward improving sustainability and eco-efficiency, as a method focused on requirements.

The results will address, firstly, the issue regarding whether a method such as bio-inspired stimulus fosters creative solutions sufficiently. The answer to these questions is relevant to the product design field, since it will help when it comes to selecting the appropriate method according to the priorities of the design: creativity (random stimuli) or requirement-solving (biological stimuli).

2. Literature review

2.1. Circular design

Important strategies that facilitate the principles of circular economy can be applied from ecodesign (Ellen MacArthur Foundation & McKinsey, 2015). This involves combining product design strategies to maintain the function and the product value at the highest level (Bocken at al., 2016) for as long as possible while also minimizing waste by facilitating recycling, remanufacturing and reuse (Evans & Bocken, 2014), (Saunders et al., 2009). MacArthur (2013) defined circular economy as “An industrial system that is restorative or regenerative by intention and design. It replaces the ‘end of life’ concept with restoration, shifts towards the use of renewable energies, eliminates the use of toxic chemicals, which impair reuse, and aims for the elimination of waste through the superior design of materials, products, systems and, within this, business models” (p. 07). Geissdoerfer et al. (2017) also defined circular economy as a regenerative system in which resource input, waste and losses are minimized by slowing down, closing and narrowing the material and energy loops. This can be achieved through durable design, repair, reuse, remanufacturing, refurbishment, and recycling. But those same authors also claimed that circular economy is an emerging topic that has attracted increasing research interest, but there is still no total consensus regarding the similarities and differences between the concept of circular economy and sustainability, even though there are some studies talking about this topic, such as Ávila-Guitérrez et al. (2019), Rodriguez-Anton et al. (2019), Prieto-Sandoval et al. (2018). This lack of a common definition could, therefore, be blurring the conceptual contours of circular economy and constraining the efficacy of its use.

In any case, interest in this topic has led to the development of a large number of ecodesign and circular strategies and methods aimed at facilitating the integration of environmental aspects into the product development process (Bocken et al., 2016), Bauman et al., (2002), Byggeth & Hochschorner (2006), den Hollander et al. (2017), Rossi et al. (2016). Hence, according to the classification proposed by Rossi et al.(2016), there are tools for life cycle assessment, like LCA (ISO, 2006) or Circularity Indicator (2020); graphic tools, like LiDS Wheel (Brezet & van Hemel, 1997) or Circular Economy Toolkit (Evans & Bocken, 2014); checklists, like the Eco-design checklist (Tischner at al., 2000) and the Ten Golden Rules (Luttropp & Lagerstedt, 2006); user-centered methods, like Life Cycle Planning (Kobayashi, 2006); methods derived from other tools, like the E-QFD (Davidsson, 1998) or the G-QFD (Bovea and Wang, 2005); and methods for eco-innovation, like the TRIZ eco-guidelines (Russo & Regazzoni, 2008) or biomimicry (Cohen & Reich, 2016). Although there are several methods for assessing circularity, most of them are focused on fully developed products, rather than concepts. This is due to the fact that, at the conceptual stage, the details of the products have still not been defined. This fact makes the tools using parameters difficult to apply in concept assessment, such as those related to aspects of production or with exact dimensions or weights, which have still not been determined at the conceptual stage of product development. Furthermore, numerous methods focus only on specific aspects of the circular economy. Consequently, it is difficult to evaluate circular economy in product concepts with the existing methods (Royo et al., 2020), (Ruiz-Pastor et al., 2019).

Although there is no standard method for evaluating circularity in products (European Environment Agency, 2016), there are methods or tools for helping this implementation of circularity. Some authors have already developed collections of these metrics, as for example in (Mesa et al., 2018), (Parchomenko et al., (2019), (Saidani et al., 2019), (Vinante et al., 2021). Among these metrics, Table 1 shows the ones that are most extended in the literature, and are also explained in more detail in Ruiz-Pastor (2022).

Table 1. Main metrics currently existing for assessing circularity.

Metric (author)	**Parameters used for measuring circularity**
Material Circularity Indicator (MCI) (MacArthur & Granta, 2015)	Material reuse, recycling, and efficiency. Lifespan and functional unit.
Circularity Calculator (IDEAL&Co & MacArthur, 2020)	Materials, production, costs, usage, and maintenance.
Circular Economy Toolkit (Evans &	Design and manufacturing, use, materials,

Bocken, 2014)	and product-service.
Circular Design Tool (Moreno et al., 2017)	Life cycle, user, conservation, and development.
Eco Compass (Fussler & James, 1996)	Materials, use, sustainability, and product-service.
LiDS Wheel (Brezet & van Hemel, 1997)	Production, distribution, lifetime, and impact.

2.2. Creative design

While various definitions of creativity have been established over time, creativity in broad terms is the ability to approach a problem differently, restructuring it in order to arrive at new solutions and possibilities that had not previously been reached (Linsey et al., 2008). In the work of Oman et al. (2013), creativity is defined as the process of evaluating a problem in an unexpected or unusual way to generate novel ideas, innovation thus being the creativity that presents utility to impact society. It could be said that creativity is the response to a problem in a way that is novel and appropriate, as well as useful and correct (Amabile, 1983). This is carried out through a process in which a subject uses his or her abilities to generate useful and novel solutions and products (Chulvi & González-Cruz, 2016).

The work of Alves et al. (2007) showed the ways in which creativity has been conceptualized over time: the individual personality, the actual process of generating new ideas, the results of the creative process, and the environment. Being able to assess creativity is very important for a correct detection of the aspects in which the product is less creative and thus to help its development (Jordanous, 2012). By measuring creativity at the conceptual design phase, designers have the opportunity to choose the appropriate design proposal in an effective way (Oman et al., 2013). Consequently, there are numerous methods for assessing product creativity. Table 2 shows some of the most representative in the field.

Table 2. Representative metrics for assessing product creativity.

Metric (author)	**Parameters used to measure creativity**
Moss (Moss, 1966)	● Utility ● Unusualness
CPSS (Besemer & O'Quin, 1989)	● Novelty ● Resolution ● Style
SAPPhIRE (Chakrabarti et al., 2005)	● Novelty
Sarkar & Chakrabarti (Sarkar & Chakrabarti, 2011)	● Utility ● Novelty
López-Forniés et al. (2017)	● Novelty ● Usefulness ● Feasibility
Ranjan et al. (2018)	● Degree of requirement satisfaction ● Novelty

3. Research Questions

This particular research is based on a main research question:

- Can biomimicry, used as "guided" stimuli, encourage creativity as well as "random" stimuli?

And, if this is not the case,

- Does a bio-inspired stimulus promote circularity to a sufficiently greater extent than a random stimulus to compensate for the loss of creativity with respect to the random method?

Solving these research questions will give an insight into how to select the most appropriate design approach (creativity or requirement-solving). This will help to establish the priorities of the first design stages and to balance the creativity and the fulfillment of the requirements of the design solutions obtained.

4. Methodology

In order to work with the approaches to be studied in this research, two design methods focused on the idea generation process were selected. These two methods have been used in the experiment that was conducted. The first is based on the principles of biomimicry (requirement-solving approach), through the Life's Principles play deck from Biomimicry 3.8 (2019). The second method is random stimuli (creativity approach). The two methods are more extensively explained in Sections 4.1 and 4.2.

4.1. Biomimicry method

Biomimicry refers to the process of using nature's efficient design solutions to inspire engineering innovations (Wadia & McAdams, 2010). There are several options that provide biomimicry inspiration, such as Animal Crackers (Grossman, S., Lloyd, 2006), the Life's Principles play deck cards of (Biomimicry 3.8, 2019), (Russo & Regazzoni, 2008) or the Ask Nature database of (The Biomimicry Institute, 2018). For this experiment, we selected the Life's Principles play deck from Biomimicry 3.8 (Figure 1). Nine cards were taken randomly from this deck, with the aim of ensuring that all the participants had the same biomimicry stimuli for inspiration. The order in which each biomimicry card was provided to the individuals was randomized, so that the order of appearance of the stimuli would not condition the designer's inspiration.

Figure 1. Nine cards extracted from the Life's Principles Play Deck, © Biomimicry 3.8 (Biomimicry 3.8, 2019).

4.2. Random stimuli method

The creative method used in this research was random external stimuli (Eberle, 1996), which has been used by several researchers, such as (Altshuller, 1999; Chakrabarti & Tang, 1996; Howard et al., 2011, 2008). Like (Howard et al., 2011), in our study nine images were taken randomly from a popular online image bank by randomly generating them in the placeholder (http://lorempixel.com/500/500) and then they were printed on cards to make a deck. The intention was for all the participants to receive the same random stimuli, so as to avoid the possible effect of different stimuli received by each individual. In any case, the deck was shuffled before each use in order to randomize the order of the stimuli.

The random images that were given to the participants can be seen in Figure 2.

Figure 2. Random external stimuli images.

4.3. Design of the experiment

The practical experiment was presented as a workshop which was attended by twelve students from the Master's Degree in Product Design and Engineering of the University of Aveiro (Portugal). There were 5 males and 7 females, with a mean age of 23, SD = 1.64. All of them had the same level of training and experience in design engineering and circular economy. None of the students knew the methods used before the experiment, thus their starting point regarding the features of the experiment was the same.

The participants were invited to participate in a workshop at the same time. In the first part of the workshop, the researchers provided them with a general outline of the objective of the workshop and the tasks included in it. Participants were asked to sign a consent and data protection form. This research complied with the American Psychological Association Code of Ethics and was approved by the Institutional Review Board at the Universitat Jaume I. Informed consent was obtained from each participant (CD/44/2019). Finally, they took part in a warm-up activity, consisting in selecting a "secret word" and drawing it in groups using the same marker attached to strings that restricted its movement. The other groups, in turns, therefore had to guess what they were drawing. This activity was carried out in order to warm up the creativity of the participants, in this way diminishing the design fixation of the students and helping to reduce inhibition (Hu et al., 2016).

After that, they were seated separately at individual desks and provided with drawing material. They were then asked to solve two different design problems, each with one of the prescribed methods: biomimicry and random stimuli. The order in which the problem and method were presented was combined so as to avoid a possible interaction among the results following the arrangement shown in Figure 3 (below).

Between the two problems, participants were given a 15-minute break in order to avoid fatigue, which could affect the results. Thus, the schedule of the experiment was as follows (Figure 3):

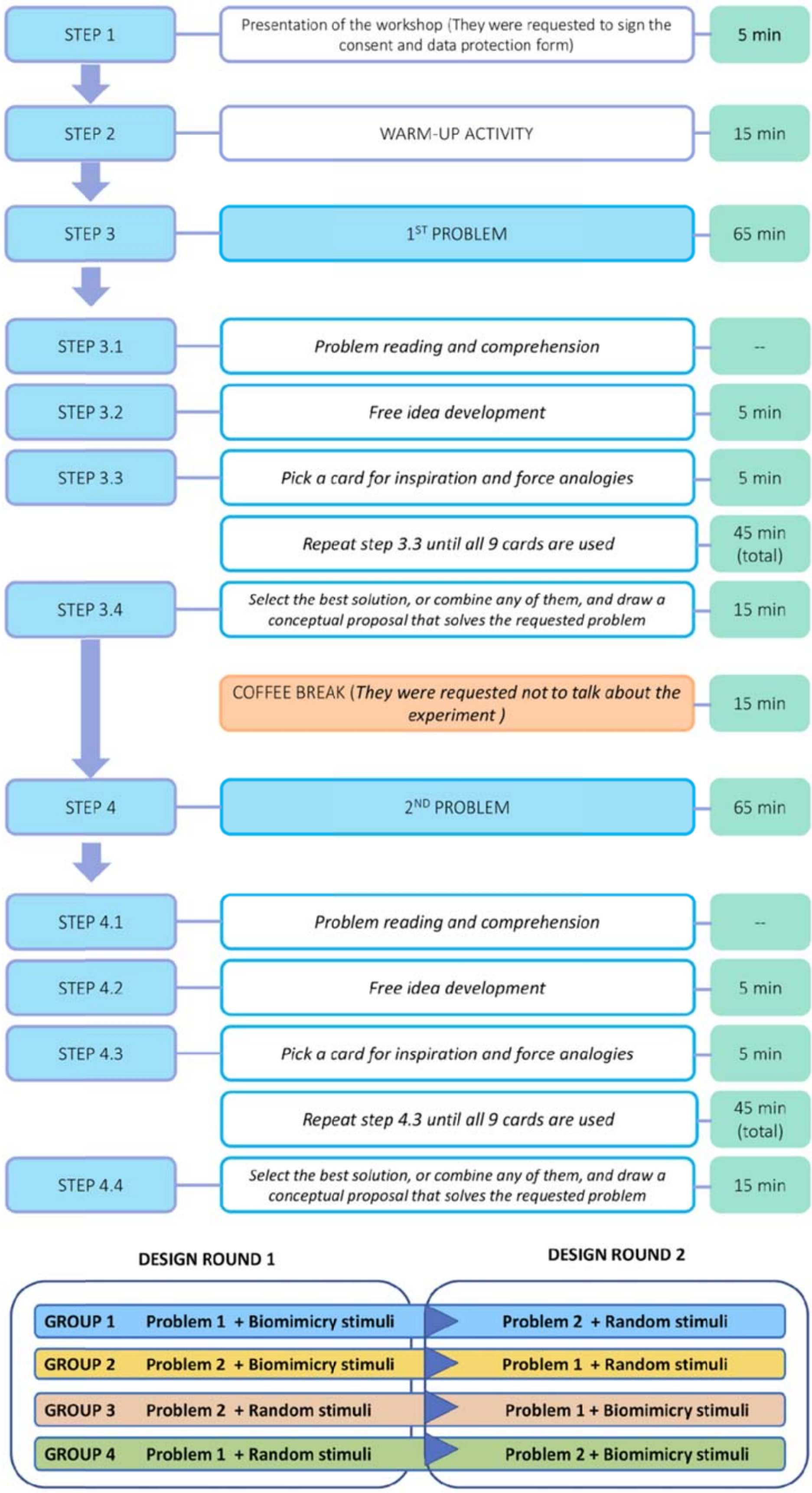


Figure 3. (Top) Schedule of the workshop and problems and (bottom) stimuli according to the group.

For this experiment, 50 minutes was considered to be enough time for idea generation, following the recommendations of (Howard et al., 2009, 2011, 2008), who claimed that idea generation remains mostly constant during the first 60 minutes, although it starts to decrease slowly and steadily after 30 minutes. The stimuli were provided individually, asking the participants to take a new card every five minutes. The objective of this was to keep the randomness, and thus ensure that the stimuli were not in the same order for all participants.

The briefs for the problems were intended to be short, in order to avoid fixation and narrow creativity of the results. In any case, as design objectives, the participants were asked to ensure the solutions were creative and circular, so as to avoid common and/or non-circular solutions that could solve the problem in any case. The type of products were not selected with any relationship with the type of cards or with the methods applied, thereby fostering randomness. The two problems were established according to the knowledge of the participants, and their familiarity with the issues to solve.

The following statements were given to the students:

- Problem 1: Design an innovative outdoor refuge element for people, following the principles of CE.
- Problem 2: Design an innovative set of elements to transport food when away from home, following the principles of CE.

As a result of the experiment, 12 concept proposals were obtained to solve each of the problems, giving a total of 24. Two examples of the results obtained (one for each problem) can be seen in Figures 4 and 5.

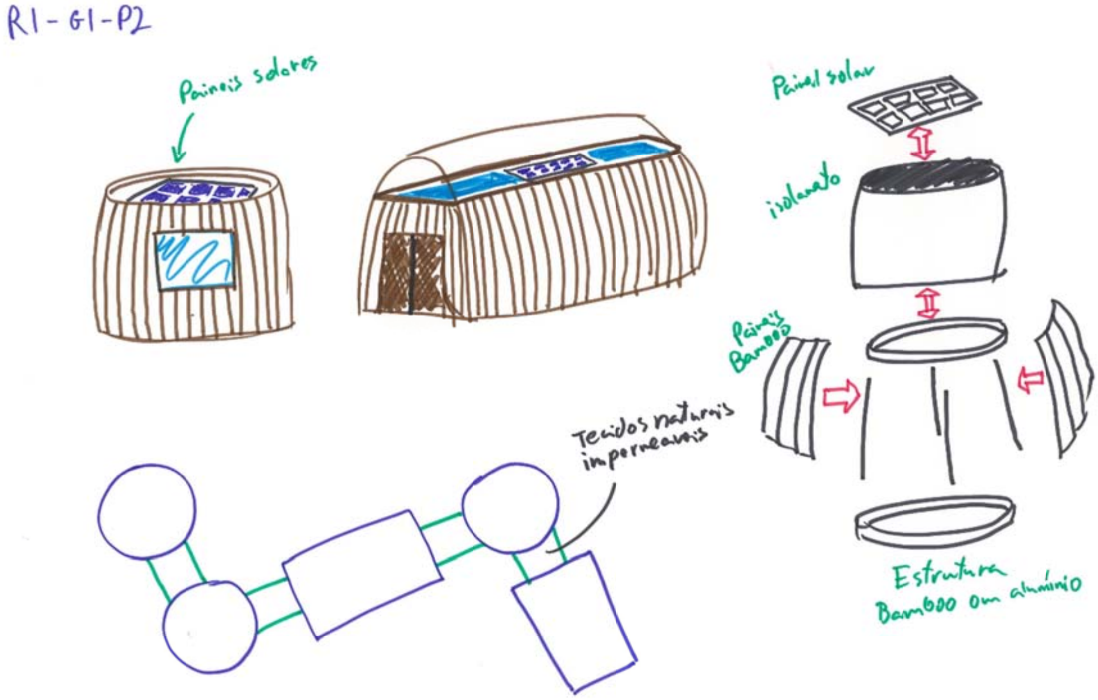


Figure 4. Example of solution for refuge element.

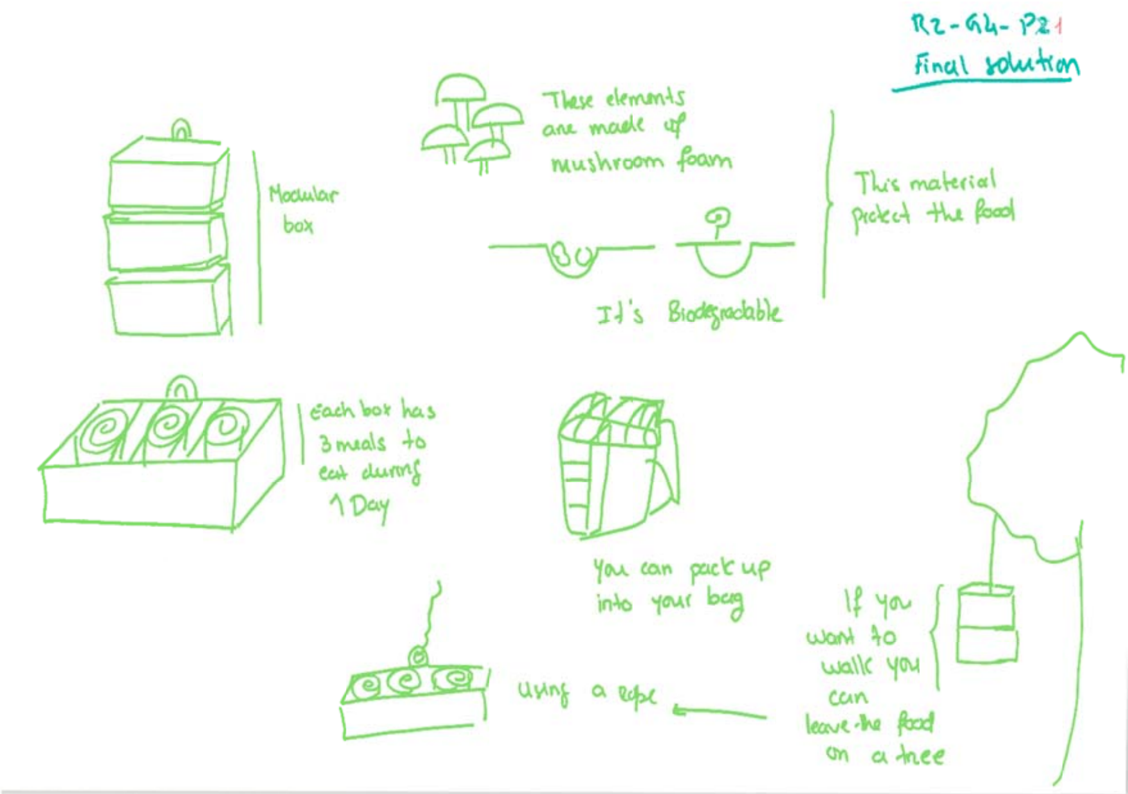


Figure 5. Example of solution for element for transporting food.

4.4. Metric for creativity assessment

Looking to evaluate the concepts with a recent, complete and well positioned creativity metric in the literature (Chulvi et al., 2021), (Ruiz-Pastor et al., 2021), (Vallet & Tyl, 2021), the creativity of the concepts obtained was assessed using the metric proposed by López-Forniés et al. (2017). This metric measures creativity as the combination of three factors: novelty, usefulness, and feasibility. In their metric, López-Forniés et al. determined that each dimension would be assessed on a 4-point scale with values within a range between 0.1 and 1. The same authors indicated that this range was deliberately prevented from starting at 0 in order to avoid null assessments that would equate several cases with distinct values in the other two factors different from the minimum. Therefore, the range starts at 0.1 to induce a strong decrease in the evaluated factor and to evidence its low contribution to the creative output. The criteria followed to evaluate the factors are indicated in Table 3.

Table 3. Criteria of the metric of López-Forniés et al. (2017).

Score	Meaning	Definition
1	High novelty	There is no other product or similar solution on the market
	High usefulness	It solves an existing problem in an alternative way
	High feasibility	Easy to achieve, no investment or technical changes to the manufacturing process needed
0.7	Medium novelty	It could be a new solution on the market thanks to some conceptual differentiation
	Medium usefulness	It solves certain aspects of the solution
	Medium feasibility	A few changes in the manufacturing process may be needed, requiring some investment
0.3	Low novelty	It exists on the market but for other applications or is new for a specific application
	Low usefulness	It solves part of a problem under certain circumstances
	Low feasibility	Relevant changes in the manufacturing process may be needed, requiring important investment
0.1	Without novelty	It exists for the same application, but it differs in some aspects

	Without usefulness	It solves part of a problem under certain circumstances and that problem has already been solved in an alternative and simpler way
	Without feasibility	The changes needed are difficult to achieve, and the need for investment is very high

The value of creativity is calculated for each concept by multiplying the three resultant values. Thus, the creativity score ranges from 1 (most creative) to 0.001 (least creative).

4.5. Metric for circularity assessment

The circularity of each of the proposals was evaluated, in this case, with the tool designed by (Moreno et al., 2017), (Vinante et al., 2021). This tool evaluates the circularity of design proposals according to 46 parameters related to circular economy. It was chosen for being one of the few metrics in the literature designed to assess circularity in concepts and one of the most complete in terms of parameters (Ruiz-Pastor et al., 2021), (Royo et al., 2021). The parameters used in the metric, in turn, are classified into the following topics: Resource conservation (design for energy conservation and for material conservation and waste disposal), Life cycles (end-of-life; design for optimizing/extending product life and for multiple life cycles), Whole system design (design for sustainability), Customer (design for users), and Development (design for the present towards the future). Inside each of the topics, the metric provides several parameters weighted to calculate the final score according to their general importance ("Factor" in Table 4). The tool has been described by the authors for evaluating concepts, but at the same time has some parameters that are too specific for the proposals being assessed, which have been estimated according to the information available in the design solutions. Nevertheless, among the existing tools considered it is the most suitable for evaluating the proposals generated in the experiment, since it is one of the most adaptable to concepts and the most complete in terms of parameters and circular economy as a global concept.

To rate each of the design proposals, a score between 0 and 5 was assigned to each of the parameters. The authors of the tool (Moreno et al., 2017) also assigned an importance factor to each of the parameters, so the next step was to multiply the score given to each parameter by its importance factor. For example, the importance factor of "allow reuse" is 4.3, so a concept that has a score of 4 for that parameter will have a final score of 17.2 (4 × 4.3). In order to obtain the final score, the total scores of each of the parameters are added up. Therefore, depending on the different importance factors provided by the metric, the score of a concept can be between 0 (less circular) and 787.5 (more circular). Table 4 shows the example of the circularity score of the concept R2-G4-P1.

Table 4. Example of circularity score.

CIRCULAR DESIGN ASPECT	**DfX Approach**	**STRATEGY**	**FACTOR**	**SCORE**	**TOTAL STRATEGY**
Resource conservation	Design for energy conservation	Use clean energy consumption	3.6	3	10.8
		Reduce energy consumption in manufacture (eliminate yield losses)	3.3	0	0
		Improve manufacture (production steps, supply chain)	3.5	0	0
		Use processes suitable for low scale production	2.5	0	0
	Design for material conservation and waste disposal	Select the best materials (non-toxic, pure if possible)	3.8	5	19
		Choose local materials (non-rare to avoid scarcity)	3	0	0
		Consider a healthy material flow	3.7	4	14.8
		Eliminate unnecessary parts and sub-assemblies	2.6	1	2.6

		Reduce material (light weighting)	2.8	0	0
		Reduce or eliminate packaging	3.2	0	0
		Reduce the size of components (miniaturize)	2.6	0	0
		Avoid composites and coating (difficult to separate materials)	4.3	4	17.2
		Avoid toxic adhesives, use easy-mechanic joints (fasteners, visible joints)	3.4	4	13.6
		Use pure materials to allow biodegradability	3.2	5	16
Life Cycles (end-of-life)	Design for optimizing / extending product life	Ensure reliability (quality)	3.8	0	0
		Allow reusability	4.3	3	12.9
		Encourage maintenance (repair/refurbish)	4.4	0	0
		Ease assembly/disassembly	4.3	3	12.9
		Standardize parts for compatibility (modularity)	4.1	5	20.5
		Remanufacture	4	0	0
	Design for multiple life cycles	Recover material (easy to clean, collect and transport)	4.1	1	4.1
		Allow cascade use	3.8	1	3.8
		Motivate the user to recycle	2.9	0	0
		Ensure availability of spare parts	4	0	0
Whole System Design	Design for sustainability	Shift the ownership of products into a service (swap, rent, share)	4.2	0	0
		De-materialize products into digital platforms	3.4	0	0
		Allow upgradability and flexibility to adapt	3.9	2	7.8
		Strengthen local industry	3.3	0	0

		Create regenerative systems (biomimicry)	3.3	0	0
		Care about social impact	3.5	1	3.5
		Create wealth through a good business practice (improve cost-benefit relationship)	3.6	0	0
		Develop a trace-and-return system	3.8	0	0
Customer	Design for users	Customize to the wants and needs of each person	2.8	2	5.6
		Enhance durability (avoid built-in obsolescence)	3.9	2	7.8
		Develop attachment/loyalty (experience, meaningful design)	3.3	0	0
		Reduce waiting times in delivery to consumer	2.3	0	0
		Based on long-lasting trends, no ephemeral fashion (timeless aesthetics)	2.7	2	5.4
		Implement poka-yoke principles to ease use	2.6	0	0
Development	Design for the present towards the future	Use mobile technologies	3.1	0	0
		Use Machine-to-Machine communications (M2M)	3.2	0	0
		Use cloud computing	3.2	0	0
		Use social media technology	2.6	0	0
		Use big data analysis	3.3	0	0
		Use new material (intelligent, organic)	3.2	4	12.8
		Use 3D printing (avoid subtracting technologies)	3	0	0
		Create multi-functional teams to consider different aspects in the design	4.1	0	0
			TOTAL		**191.1**

4.6. Statistical analysis considerations

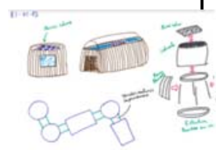
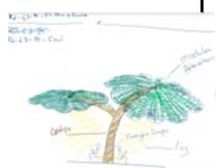
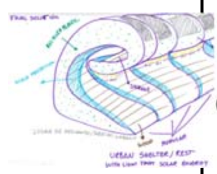
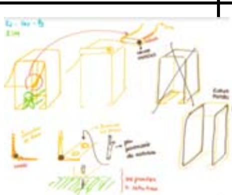
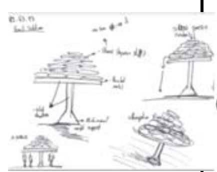
The statistical analysis was performed with the software SPSS, PASW Statistics version 25 (IBM Corporation). The circularity and creativity scores obtained by the results were analyzed in order to answer the research question.

First of all, the Shapiro-Wilk test was run to check whether the distribution of the two groups is normal. After that, an ANOVA test was performed for the creativity and circularity results. All the results were obtained with a significance level of 0.05.

5. Results

The final conceptual proposals were assessed in terms of creativity and circularity, as indicated in previous sections. For this proposal, two experts evaluated the different concepts. The experts were both PhDs with experience in the field of Engineering Design and with previous knowledge of creativity and circularity assessment. The evaluation carried out by the experts was blinded, and furthermore the intraclass correlation among the two evaluations was calculated in order to validate the assessment carried out and in order to see the relationship among both results. The coefficients of intraclass correlation between the experts were $r = 0.998$ for circularity assessment and $r = 0.711$ for creativity assessment. Within the creativity factors, the correlation coefficients were $r = 0.90$ for novelty, $r = 0.886$ for usefulness, and $r = 0.784$ for feasibility. Table 5 shows the resulting creativity values, as the result of multiplying the novelty, usefulness, and feasibility scores. Table 5 also shows the values of the circularity assessment.

Table 5. Scores of the conceptual solution proposals.

Concepts generated with random stimuli								Concepts generated with biomimicry cards					
		Novelty	Usefulness	Feasibility	Creativity	Circularity			Novelty	Usefulness	Feasibility	Creativity	Circularity
R1-G4-P1		0.1	1	1	0.1	97.5	R1-G1-P1		0.3	1	0.7	0.21	170.7
R1-G4-P2		0.7	1	0.3	0.21	163	R1-G1-P2		0.3	1	0.3	0.09	195.2
R1-G4-P3		0.7	0.3	0.3	0.07	79.9	R1-G1-P3		0.7	1	0.7	0.49	282.2
R2-G2-P1		0.3	0.3	0.7	0.07	71.6	R2-G3-P1		0.1	1	1	0.1	131.2
R2-G2-P2		0.1	0.7	0.7	0.05	84.1	R2-G3-P2		0.7	0.7	0.3	0.15	137.4
R2-G2-P3		0.1	1	1	0.1	130.3	R2-G3-P3		0.1	0.7	0.7	0.05	265.6

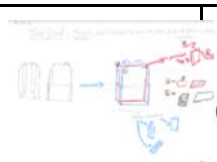
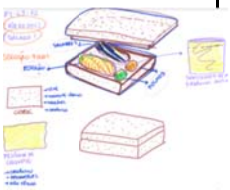
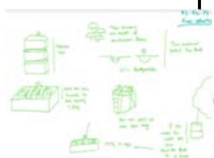
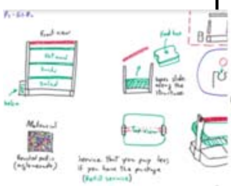
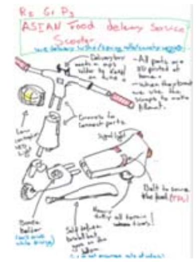
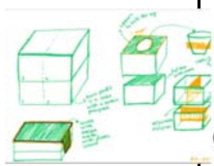
R1-G3-P1		0.1	1	1	0.1	124.7	R1-G2-P1		0.3	0.3	1	0.09	174.5
R1-G3-P2		0.7	0.7	0.3	0.15	127.6	R1-G2-P2		0.3	1	1	0.3	168.5
R1-G3-P3		0.1	0.7	0.7	0.05	125.3	R1-G2-P3		0.1	1	0.7	0.07	141.3
R2-G1-P1		0.1	0.3	1	0.03	108	R2-G4-P1		0.1	1	1	0.1	191.1
R2-G1-P2		0.3	0.7	0.7	0.15	232.7	R2-G4-P2		0.7	1	0.3	0.21	182.5
R2-G1-P3		0.7	0.3	0.3	0.07	139.3	R2-G4-P3		0.7	0.3	0.3	0.07	179.3

Figure 6 shows the box and whiskers plot of the creativity results, according to the method used to solve the problem. In the figure it can be seen that the median value of creativity achieved using biomimicry is slightly higher and more dispersed than when using random stimuli. The concepts obtained with the random stimuli present a mean creativity score of 0.09, with a standard deviation of 0.055, while those achieved with the biomimicry stimuli have a mean creativity score of 0.16, with a standard deviation of 0.137. The same occurs in the case of novelty, where the results obtained using random stimuli present a mean of 0.25 and a standard deviation of 0.228, while the mean when using biomimicry is 0.30, with a standard deviation of 0.256. The mean and standard deviation of usefulness when using random stimuli (M 0.65, SD 0.239) are also lower than when using biomimicry (M 0.78, SD 0.266). On the other hand, in the case of feasibility, the mean and the standard deviation are M 0.70, SD 0.276 for random stimuli; and M 0.73 SD 0.290 for biomimicry.

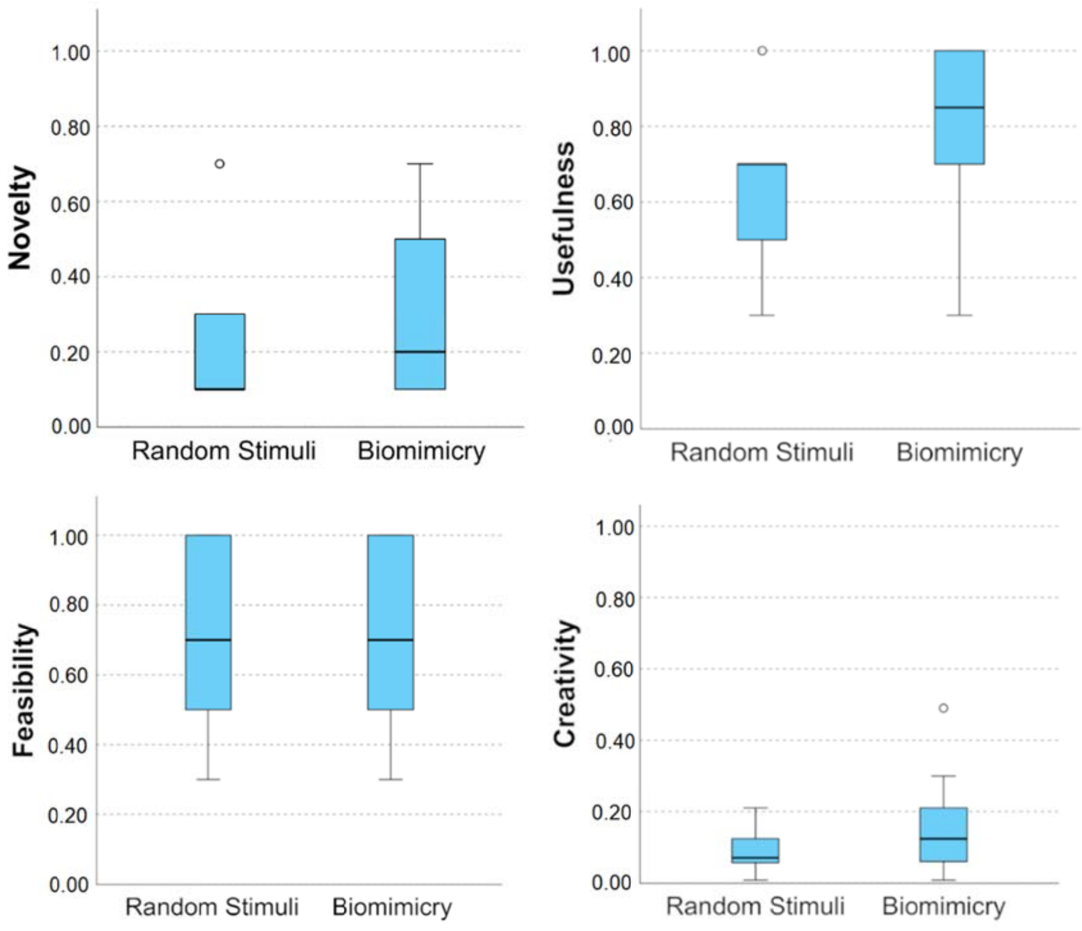


Figure 6. Creativity and its factors distributed by type of stimuli.

The concepts developed with the random stimuli show a mean circularity score of 123.66, with a standard deviation of 43.55, while those that were obtained with the biomimicry stimuli have a higher mean circularity score of 184.95, with a standard deviation of 46.49. The box and whiskers plot of circularity (Figure 6) shows the median and dispersion of the results.

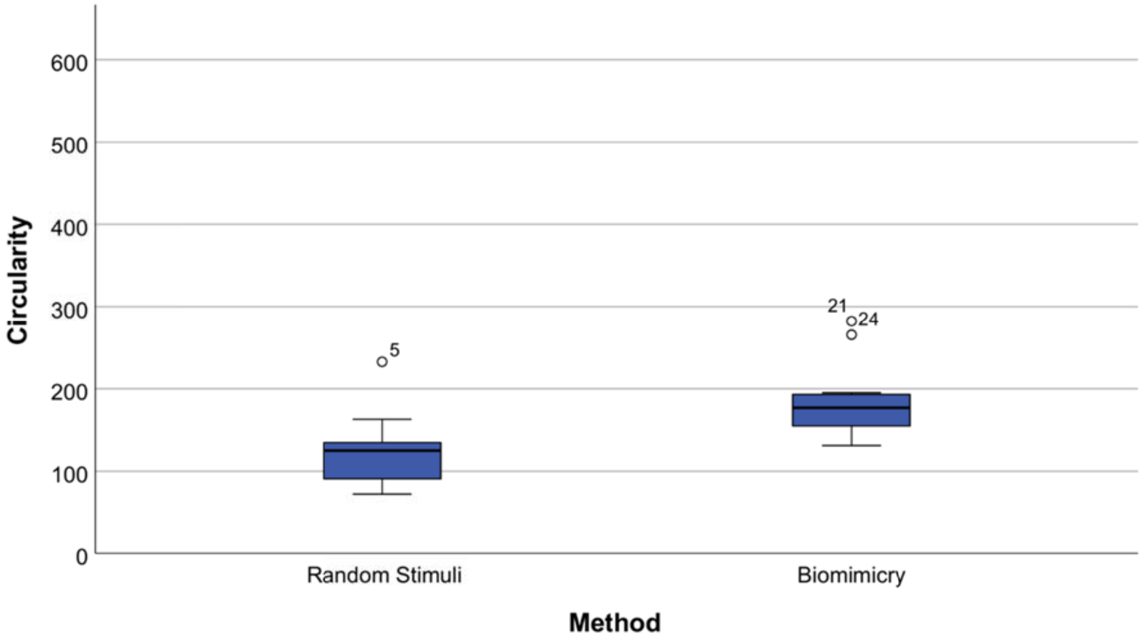


Figure 7. Circularity distributed by type of stimuli.

Since there are fewer than 50 solutions, a Shapiro-Wilk test was carried out to calculate the type of distribution that the scores follow. The results show that circularity scores follow a normal distribution, while creativity scores and their factors present a non-normal distribution.

- W(24) = 0.70, p = 4.2E-4 (novelty)
- W(24) = 0.80, p = 2.9E-4 (usefulness)
- W(24) = 0.79, p = 2.2E-4 (feasibility)
- W(24) = 0.81, p = 3.6E-4 (creativity)

- $W(24) = 0.88$, $p = 0.238$ (circularity)

Following this, to determine whether the creativity results are affected by the kind of stimuli used, a Kruskal-Wallis analysis was performed and the results show that, for creativity, there is no difference in the results depending on the method used. For novelty, usefulness, and feasibility there are also no significant differences.

- Creativity: $H(1) = 1.569$, $p = 0.210$
- Novelty: $H(1) = 0.229$, $p = 0.632$
- Usefulness: $H(1) = 2.052$, $p = 0.152$
- Feasibility: $H(1) = 0.077$, $p = 0.782$

In the case of circularity, a Student's t-test was also performed. In this case the results show that there is a difference between the results obtained with random stimuli and the results obtained with the biomimicry cards ($p = 2.7743E\text{-}8$) with a 95% confidence interval.

6. Discussion

The analyses of the results show similar results in terms of creativity, since the mean values are 0.09 for random stimuli results and 0.16 when using the biomimicry cards as guided stimuli. Consequently, there is no statistically significant difference between the two methods. This answers the first research question posed, regarding whether a method such as bio-inspired stimulus is sufficiently effective to obtain creative solutions. This may suggest that the external stimuli provided to enhance designers' creativity can be predefined or pre-selected by the facilitator according to the requirements of the design problem. Thus, the stimulus is still random for the designer, who is previously unaware of it, and so it has the same effect in terms of awakening creativity during the design process. Furthermore, both the way it is presented and the way it is applied remain the same—they are given an external stimulus and must make analogies based on this stimulus.

This suggests that it is the way the stimulus is presented, in general terms, and not the stimulus itself that can cause fixation, and thus decrease creativity. Yet, how the stimulus was presented might not be exact due to the nature of the experiment. In the case of the biomimicry cards, the stimulus was not just an image, but was accompanied by a short text. The reason for adding the text was to make sure that the stimulus was identified with a biomimicry strategy, and was not misinterpreted in any other way, since this would have invalidated the study. This different way of presenting the stimuli (image vs. text + image), on the one hand, might have caused some variation in the design results, according to some authors (Linsey et al., 2008), (Sarkar & Chakrabarti, 2008), (Borgianni et al., 2020). On the other hand, neural studies have shown that, when a creative activity is performed, the same areas of the brain are activated regardless of whether the stimulus provided (visual or written) belongs to different areas of the brain (Aziz-Zadeh et al., 2013). In any case, this could be considered a limitation of the study, and further research will be required to investigate in more depth the effect that this dimension may have had on the outcomes.

On the other hand, regarding circularity, the results obtained with biomimicry stimuli (mean score of 184.95) are significantly higher than when using random stimuli (mean score of 123.66), as expected. This endorses the use of biomimicry to potentiate circular results, as defended by many authors such as (Iustin-Emmanuel & Alexandru, 2014), (Bockholt et al., 2019). In this regard, the second research question asked whether the bio-inspired stimulus promotes circularity to a sufficiently greater extent than a random stimulus to compensate for a possible loss of creativity. This loss of creativity is usually caused by fixation (Helms et al., 2009). Since the loss of creativity has not occurred, but there has been a significant improvement in terms of circularity, this seems to indicate that a preselection of stimuli oriented towards the design requirements considerably improves the design results in global terms. In the specific case of this work, preselected cards fostering biomimicry help to better introduce these features in the ideation process, without causing fixation. That is to say, without there being a loss of creativity in the design outcomes.

Among the limitations of the study was the fact that only MSc design students were used to conduct the study. We could assume that the results may vary in the case of using expert designers. On the one hand, they have more experience in solutions applied to real life, which may lead to greater usefulness of the solutions, and even greater circularity, if their previous experience has included work in this field. But on the other hand, their experience in their field of work may close their vision to other fields. In this case, it could be considered that novel designers have a greater capacity to imagine different fictitious situations, which may lead them to more imaginative, though less feasible, solutions. Other limitations may have been the mode of data collection. In this case only the design results have been collected, but another possibility could have been to record the design process, in order to be able to analyze the behavior of the designers in the different phases of the design process and whether this affects the outcome. Interviews could also have been performed with the participants, in order to find out their perception, or personality profile tests could even have been applied to find out if the designer's own psychological profile was a variable to be taken into account. All these, of course, are new hypotheses that arise from the present study, and further research would be required to demonstrate whether these differences really exist. In any case, as all participants had the same level of experience, this is not thought to be a factor affecting the results of the present research.

7. Conclusions

According to the results of the present research, it can be said that biomimicry helps to obtain circular results and, when used in ways similar to creative techniques, does not interfere with the generation of creative ideas. That is, biomimicry, used as "guided" stimuli, is as capable of encouraging creativity as "random" stimuli, and besides it also fosters circular results. Therefore, this kind of tool can be a great aid to designers when developing circular and creative designs.

This result opens new doors to the creation of new conceptual design techniques for both creativity and circularity. Future work, therefore, can lead to the design and testing of new methods with this approach. Furthermore, if circularity is considered a "strict design requirement", this conclusion could also be opened to other specific design requirements, making it possible to break the tendency towards the decrease in creativity that designers face when they are expected to implement very strict design requirements (Cucuzzella, 2016).

The study has, however, been limited to one specific biomimicry tool, tested by a limited group of designers. Therefore, it would be interesting both to expand the sample and also to test whether this effect will occur when applying other tools for circularity used as creative design techniques. This would add greater strength to the conclusions presented in this paper. Also, the lack of tools specifically elaborated for assessing circularity in design concepts could have had an influence on the results since there are some parameters that have been estimated in the proposed concepts because they are still not defined at this design stage. Consequently, future work may involve the development or adaptation of a tool or metric for a better assessment of circularity in concepts.

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