 doi:10.20944/preprints202206.0307.v1

Article

Creating Biomimetic Examples: A Design Method with Scientific Results

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Abstract: Prospective end-users rated aptness, creativity, and innovativeness of biomimetic examples that featured different relationships to create combinations (e.g., used for) between nature and technology. Against common theorizing, similarity was not the most profound for creativity but rather appearance, being part_of, and property_of were. Creativity explained most of the variance in the level of innovation with aptness of the design in a strong supporting role. The focus of conceptualization shifted from 'creation as new things coming from new ideas' to 'innovation as new ideas leading to new things.' Results are interpreted in the Chinese context of utility. Both in education and industry, the use of 5*5 research grids with rating scales may work as a design method to develop and select functional variants during early design.

Keywords: creative relations; biomimicry; design method; creativity; innovation; aptness

1. Introduction

It almost goes without saying that design centers around creativity and innovation. Quite a number of theoretical accounts of creativity have been given (cf. Greene's 2004 '60 models') but there seems to be an overall consensus that creativity is the combination of associatively remote entities in a new way (e.g., Han, Shi, Park, Chen, & Childs, 2018): Making 'novel combinations' is the handbook definition of creativity (e.g., Albert & Runco, 1999, p. 25; Ward & Kolomyts, 2010, p. 101; also Csíkszentmihályi, 1996, p. 9). Although one may argue that to create may not necessarily be to create something new, the demand of novelty seems persistent when discussing human creativity.

Not too surprisingly, the term innovation is closely linked to being creative as concepts like novel and novelty have their root in the Latin 'innovare,' and so innovation shares with creativity that ideas are supposed to be new and fresh. On innovation, Beghelli and Jones (2022) remark that designs should be novel but also useful. Innovation pertains to 'use … in a new context, and use of a new underlying technology' (Beghelli & Jones, 2022). McCarthy, Chen, and McNamee (2018) point out a trade-off between being innovative and usefulness, which also has a cultural twist: Not anything new is considered useful in an analytic vs holistic culture. In Eisenbart, Bouwman, Voorendt, McKillagan, Kuys, and Ranscombe (2022), innovation is the implementation of design thinking to 'nurture innovation and creative capabilities;' again, both notions mentioned in one breath.

1.1. Types of relations that make up the combinations

Combination making may be at the heart of creativity with its spillover into innovative design, but on what grounds does a combination make sense? Is any combination regarded as 'creative,' 'innovative,' or 'apt?' Otherwise stated, what type of relationship between the associative remote concepts and objects make up a creative combination?

A top candidate may be the notion of similarity (e.g., Wang & Hu, 2018), which may pertain to structural aspects such as principle, meaning, and system or more surface

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aspects like form, color, and shape of attributes (Vosniadou & Ortony, 1989; Blanchette & Dunbar, 2000). In our study of biomimicry, the focus will be on structural aspects (i.e. function) rather than surface aspects of combination making.

Similarity also is foundational for analogical reasoning (Figure 1) (Gentner & Smith, 2012; Ozkan & Dogan, 2013) and in its technological implementation, in case-based reasoning systems. For instance, Cunningham (1998) states that creativity operates in "weak theory domains" (cf. 'soft constraints' in Helie & Sun (2010)), which allows for cross-domain combinations to happen more easily. The presence of 'shallow knowledge' (Cunningham, 1998) may suffice and may provide better design solutions overall.

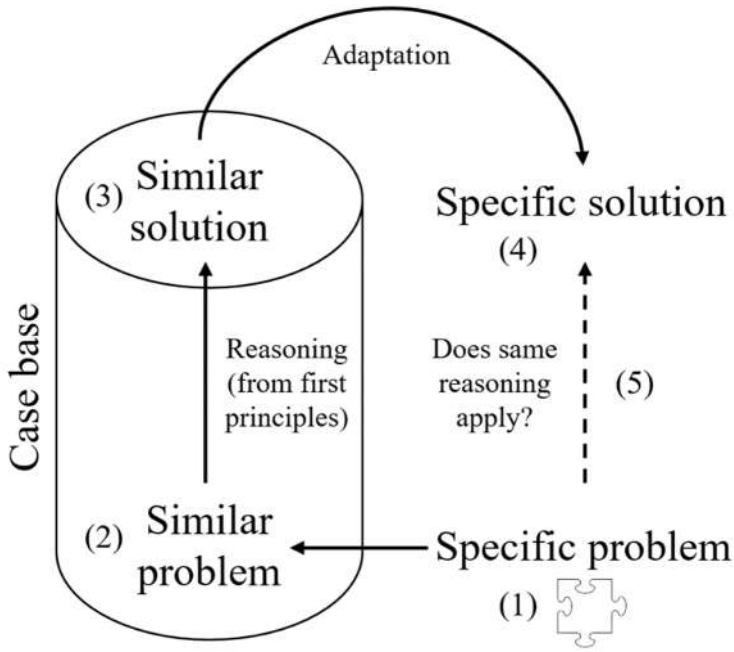

Figure 1. Case-based reasoning solves problems by analogy (after Cunningham, 1998).

Figure 1 shows the way case-based reasoning works, which resembles the way humans solve analogies. An analogy follows the structure of *old solution : old problem :: adapted solution : new problem* (A:B::C:D). From a specific problem (1), a general case base is searched for similar problems (2), which may lie in completely different domains. In Figure 2, for instance, the woodpecker-inspired axe (C.A.M.P. SpA, 1994, Premana, Italy) mimics the bird's neck arrangement for more balanced swing and a more efficient blow (Kim, Bouchard, Bianchi-Berthouze, & Aoussat, 2011).

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Figure 2. Woodpecker-inspired axe (Lodato, 2010) – similarity establishes the combination.[1].

If we apply the camp axe problem to the reasoning of Figure 1, then:

1) Current axe is imbalanced and inefficient
2) Who in nature works like an axe? (association with remote category)
3) How does the woodpecker do it?
4) Adapt woodpecker neck-shape to fit the camp axe
5) Energy absorption by new camp axe mimics that of the bird's neck

It appears that the creative combination is in the abstraction of finding similar principles in otherwise unrelated domains. However, this is not a one-to-one relationship. The similarity does not equal sameness or identity; similarity rather represents 'fuzzy resemblance' (e.g., Richter & Weber, 2013, p. 115).

Similarity may be one candidate to establish a creative combination but if we check MIT Media Lab's ConceptNet for example (https://conceptnet.io), the meaning of words

[1] Photo by Jonathan Kantor. K. Rockwood, *Biomimicry: nature-inspired designs.* Fast Company (Oct. 1, 2008): http://www.fastcompany.com/magazine/129/truly-intelligent-design.html

 doi:10.20944/preprints202206.0307.v1

in the incorporated semantic networks show many more types of relationships than just Similar_to: Is_a, Has, Part_of, Kind_of, Used_for, etc. Particularly Used_for may prepare instantiations of Unusual or Alternate uses (Wilson, Guilford, Christensen & Lewis, 1954), a particular type of creative approach.

In addressing the research question what type of relationship between entities from associatively remote domains can make a creative combination, I set up a research project in my design class, looking into a variety of relationships as potential candidates for creative and innovative designs. As spiritedly argued by Reich (2022), as designers, "we cannot play 20 questions with creativity and innovation and win," and therefore, we conducted "practice-based integrative research" (ibid.), yet capable of yielding scientific results.

1.2. Grids: attempt of a design method

To define a clear-cut case of crossover combinations that potentially produce creative and innovative design ideas, we settled for biomimetic examples or biomimicry. That way, we were sure to address the use of technology in a new context and/or the use of novel basic technology (cf. Beghelli & Jones, 2022). Biomimicry tries to imitate principles, systems, and aspects of nature (i.e. organisms) to solve certain problems, often in the technical domain (cf. Figure 2).

In the current study, we created so-called Grids by putting 5 phenomena related to plants and animals (e.g., an Armadillo's carapace – body covered in plates) in a certain relationship (e.g., Used_for) with 5 devices or technologies (e.g., a bridge), resulting into a biomimetic design idea: The body structure of armadillo is used for a bridge to roll up when a ship passes through (Figure 3).

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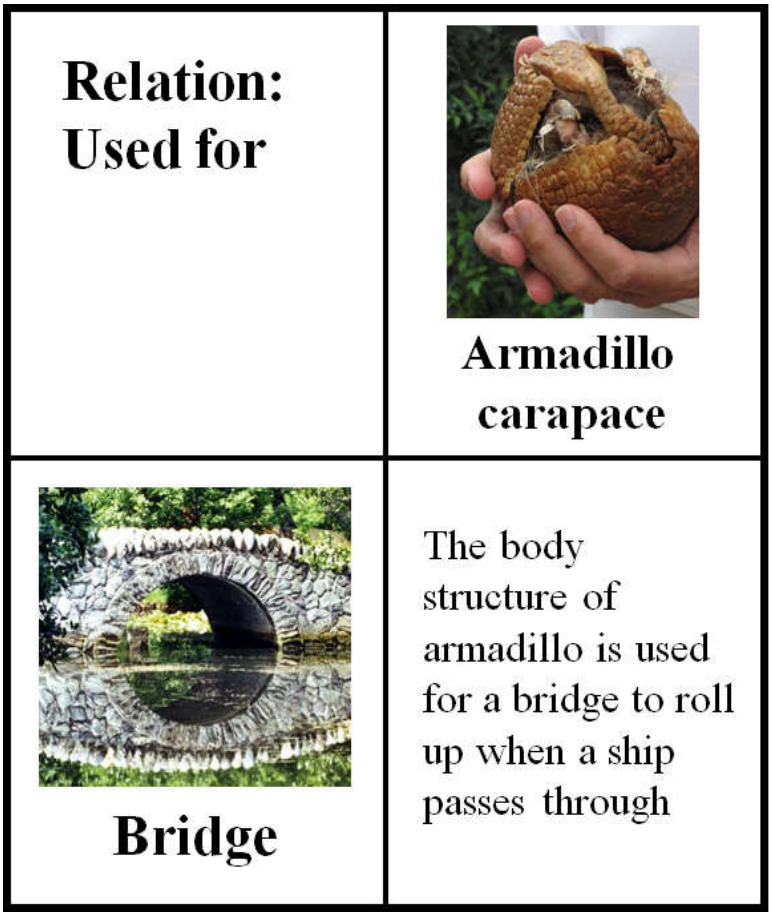

Figure 3. Grid1 (Used_for) of 25 examples, Example 01: Use armadillo body-structure for a roll-up bridge.[2].

Like this, we created 14 grids of 25 examples each, resulting into 350 biomimetic design ideas that exemplified different relations to create a combination. These examples were evaluated by a group of potential end-users of such 'new technologies' on creativeness, innovativeness, and 'aptness' (see next section).

Hypothesis 1 (H1) runs as follows: In line with prevailing theory (e.g., Wang & Hu, 2018), the relationship Similar_to should outdo the other relationships in establishing a creative combination that is deemed innovative and apt.

In countering H1, H2 says that: It is indifferent which relationship establishes the combination (i.e. H0) as long as that combination is high on creativity, less so on innovativeness and aptness.

H3: Innovation is creativity that is useful (or 'apt') (cf. Beghelli & Jones, 2022; McCarthy, Chen, & McNamee, 2018).

2. Method

2.1. Participants and Design

A total of 423 participants voluntarily joined our field experiment without receiving any reward. They filed their consent to use their anonymized data but three participants failed to rate the examples presented to them, which left us with N = 420 for analysis. According to box-plot analysis, there were 24 outliers for the three dependent variables we measured (see *Measures*), so the data set with outliers removed was n = 396 (Supplemental Files for details). Demographics of this outlier-free group were M_{age} = 29, SD_{age} =

[2] Armadillo, courtesy peachyqueen, https://morguefile.com/p/78292

Bridge, courtesy lisaleo, https://morguefile.com/p/1031416

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7.51; 169 male, 225 female, 2 other; 371 Asians, 9 Europeans, 6 Africans, 4 Australians, 5 South-Americans, 1 North-American; 61.7% at Bachelor level or beyond, the remainder followed High school or less.

Participants filled out an online survey, querying 2 Grids with 25 Examples of biomimetic design ideas each. There were 14 Grids divided into 7 Sets of two Grids (between-subjects). Each Grid exemplified a different semantic relationship between two associatively remote concepts (cf. Han, Shi, Park, Chen, & Childs, 2018), and each participant worked on two Grids, making up 50 examples per participant (within-subjects).

2.2. Procedure

After clicking the consent button in an online questionnaire, participants were exposed to a Grid of 5 pictures in a row and 5 in a column with a written explanation to the Grid (see Appendix 1). In combination, these pictures exemplified a certain relationship with each other (e.g., has_Property), visible in the upper left corner. Respondents studied the grid for a self-paced time and after clicking 'next,' each combination in a Grid was presented as a single item with three 6-point rating scales for aptness, creativity, and innovativeness. Examples with rating scales were presented in random order, different for each participant. Upon completion of the first grid, a second grid was presented, following the same procedure. After scoring the 2 × 25 examples, participants filled out three separate text boxes to write down their definition of and associations to 'apt' (box 1), 'creative' (box 2), and 'innovative' (box 3). The survey ended on querying background information such as demographics.

2.3. Apparatus and Materials

To reach a large diversity of potential end-users, the survey was made available at the following online platforms: Qualtrics, WenJuanxing, Tencent, and Questionnaire Star. Participants were invited to click the link or scan the QR code and could work online on their computer, tablet, of mobile phone.

As part of a research project, master students of design created 14 Grids, consisting of 25 cells containing examples of biomimetic ideas for industrial design engineering, systematically combining 5 qualities from the natural domain in the rows (i.e. plants and animals) with 5 industrial or consumer devices in the columns (Figure 4). The crossings contained a description of the combination, following the relationship exemplified in the Grid (e.g., 'is similar to'). Like this, 14 different Grids were developed and divided into 7 Sets, equaling 7 different between-subjects experiments:

1) Has_a, Part_of 2 Grids
2) Combined_with, has_Property 2 Grids
3) Capable_of, Appearance_of 2 Grids
4) Used_for, has_Property/different examples from Set2 2 Grids
5) Inspired_by, can_Mimic 2 Grids
6) Similar_to, Form_of 2 Grids
7) Desired_by, Symbol_of 2 Grids

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Relation is: Similar to	Face mask 	Gas Mask 	Sifter 	Water purifier 	Dialysis machine 
Baleen 	A face mask with filtering system similar to the comb-like structure of a baleen	A gas mask with a filtering element similar to the comb-like structure of a baleen	A sifter with a mesh that is similar to the comb-like structure of a baleen	A water purifier with a filter element similar to the comb-like structure of a baleen	A machine with dialysis membrane that is similar to the comb-like structure of a baleen
Sponge 	A face mask with a filtering layer similar to the cavity structure of a sponge	A gas mask with a filtering element similar to the cavity structure of a sponge	A sifter with a mesh that is similar to the cavity structure of a sponge	A water purifier with a filter element similar to the cavity structure of a sponge	A machine with dialysis membrane that is similar to the cavity structure of a sponge
Boar's nose 	A face mask with a filtering layer similar to the boar's nose, smelling harmful substance	A gas mask with a filtering element similar to the boar's nose, smelling harmful substance	A sifter with a mesh that is similar to the boar's nose, smelling harmful substance	A water purifier with a filter element similar to the boar's nose, smelling harmful substance	A machine with dialysis membrane that is similar to the boar's nose, smelling harmful substance
Algae 	A face mask with a filtering layer similar to life algae, digesting harmful substance	A gas mask with a filtering element similar to life algae, digesting harmful substance	A sifter with a mesh that is similar to life algae, digesting harmful substance	A water purifier with a filter element similar to life algae, digesting harmful substance	A machine with dialysis membrane that is similar to life algae, digesting harmful substance
Gills 	A face mask with a filtering layer similar to a gill, filtering oxygen out of the air	A gas mask with a filtering element similar to a gill, filtering oxygen out of the air	A sifter with a mesh that is similar to a gill, filtering oxygen out of the air	A water purifier with a filter element similar to a gill, filtering oxygen out of the air	A machine with dialysis membrane that is similar to a gill, filtering oxygen out of the air

Figure 4. Set6, Grid1 (Similar_to): 25 biomimetic examples with their relation printed in the upper left corner.[3].

[3] Face mask, courtesy bango, https://morguefile.com/p/1165415

Gas mask, courtesy cheriedurbin, https://morguefile.com/p/962305

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We made sure to combine 5 different entities in each row and column, not variants of the same thing (e.g., not: gorilla, chimpanzee, baboon, mandrill). We also made sure the addition was functional and not a mere 'decoration' (e.g., not: a face mask with a monkey face printed on it). We focused on biomimicry so the function was integrated in the design idea (e.g., a face mask with whale-baleen filtering-system).

Figure 5. Set7, Grid1 (Has_a): One trial consisted of a single combination with the relationship explicated.[4].

Each trial in an experiment offered a 'mini grid' of one natural entity with one device or technical structure and a description of the combination in the crossing cell (Figure 5). Respondents would score each mini grid for three design dimensions (see next).

2.4. Measures

Sifter, courtesy photojock, https://morguefile.com/p/206170

Water filter, courtesy Anna, https://ef3bdec6-1d66-4b16-9826-6e44151e28b1?rule=ecg_mp_eps$_83.jpg

Dialysis machine, Wikimedia, Hemodialysis_machine_INNOVA.jpg

Humpback, courtesy matthew_hull, https://morguefile.com/p/77807

Sponge, courtesy sideshowmom, https://morguefile.com/p/58159

Boar, courtesy dieraecherin, https://morguefile.com/p/175847

Algae, courtesy Deaboots, https://morguefile.com/p/1118795

Shark, courtesy GaborfromHungary, https://morguefile.com/p/1036525

[4] Octopus, courtesy MarcusL, https://morguefile.com/p/1019779

Lightbulb, courtesy imagine2009, https://morguefile.com/p/633046

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Participants scored 50 biomimetic examples for their level of aptness, creativity, and innovativeness. The examples were presented as a mini grid of text and images (Figure 5), followed by a Likert type item with a 6-point rating scale (1 = totally disagree, 6 = totally agree). Participants followed their own intuitions and did not receive any prior conceptualizations. A sample item (Combined_with) follows next:

- I find the idea to combine the special protection of a peanut shell with a baby swaddle…

apt

Totally disagree | Disagree | Disagree a little | Agree a little | Agree | Totally agree

1 ------- 2 ------- 3 ------- 4 ------- 5 ------- 6

creative

Totally disagree | Disagree | Disagree a little | Agree a little | Agree | Totally agree

1 ------- 2 ------- 3 ------- 4 ------- 5 ------- 6

innovative

Totally disagree | Disagree | Disagree a little | Agree a little | Agree | Totally agree

1 ------- 2 ------- 3 ------- 4 ------- 5 ------- 6

Apart from investigating creativity and innovation, aptness of the biomimetic ideas was included as a precursor to the result being useful in practice (cf. Beghelli & Jones, 2022). Yet, to understand what each of these single-item measures meant, participants were asked to:

- Please write no more than 10 sentences on what you think *aptness* is about.
- Please write no more than 10 sentences on what you think *creativity* is about.
- Please write no more than 10 sentences on what you think being *innovative* is about.

Additionality, participants indicated Gender (male, female, other), Age, Education level, and geographical Area (e.g., Asia, Europe).

3. Analysis and Results

To test the hypotheses on creative relations between associatively remote categories, I calculated Mean Aptness, Mean Creativity, and Mean Innovativeness from the ratings of $N = 420$ participants, finding 24 outliers, and continuing the analyses with $n = 396$. Pearson correlations for Mean Aptness, Mean Creativity, Mean Innovativeness and Gender, Age, Education, and Area did not reveal significant correlations between the three dependents and any of the background variables. Background variables will be discarded in further analyses.

Linear regression of Mean Aptness ($M_{apt} = 4.31$, $SD_{apt} = .64$) and Mean Creativity ($M_{cre} = 4.30$, $SD_{cre} = .60$) on Mean Innovativeness ($M_{inn} = 4.34$, $SD_{inn} = .62$) showed that the model was significant: $F_{(2,393)} = 1398.89$, $p = .000$. Together, Mean Aptness and Mean Creativity explained Mean Innovativeness with $R^2 = .88$. For Mean Aptness, unstandardized $\beta = .22$, $t = 6.94$, $p = .000$, $r_{partial} = .33$, $r_{part} = .12$. For Mean Creativity, unstandardized $\beta = .76$, $t = 22.97$, $p = .000$, $r_{partial} = .76$, $r_{part} = .41$. Mean Creativity was the better predictor of Mean Innovativeness but Mean Aptness played a significant role as well.

Oneway MANOVA (GLM Multivariate, Pillai's Trace) for Mean Aptness ($M_{apt} = 4.31$, $SD_{apt} = .64$), Mean Creativity ($M_{cre} = 4.30$, $SD_{cre} = .60$), and Mean Innovativeness ($M_{inn} = 4.34$, $SD_{inn} = .62$) showed that multivariate effects were significant with strong effect size $V = .98$, $F_{(3,393)} = 7020.10$, $p = .000$, $\eta_p^2 = .98$.

Paired-samples t-tests indicated that for Mean Aptness vs Mean Creativity, $t_{(395)} = .12$, $p = .907$, *Cohen's d* = .006; for Mean Aptness vs Mean Innovativeness, $t_{(395)} = -1.89$, $p = .06$, *Cohen's d* = -.095; for Mean Creativity vs Mean Innovativeness, $t_{(395)} = -3.06$, $p = .002$, *Cohen's*

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d = -.154. Same values for effect sizes were obtained with Hedges' correction. Thus, Mean Innovativeness of the examples in the Grids was rated as significantly higher than their Mean Creativity, even after Bonferroni correction ($\alpha \approx .017$).

To check which type of relation was regarded as more or less Innovative, Creative, and Apt, the analysis was refined by calculating the means for (*Grid# Mean variable name*): *G1Ma, G1Mc, G1Mi, G2Ma, G2Mc, G2Mi.* According to box-plot analysis, there were 32 outliers for these six dependents in N = 420 (see Supplemental Files for details), leaving n = 388 for further analysis. Pearson correlations indicated no significant correlations for the six dependents with Gender, Age, Education, and Area, which were excluded from further analyses.

Linear regression of *G1Ma* (M_{G1apt} = 4.30, SD_{G1apt} = .64) and *G1Mc* (M_{G1cre} = 4.32, SD_{G1cre} = .60) on *G1Mi* (M_{G1inn} = 4.34, SD_{G1inn} = .61) pointed out that the model was significant: $F_{(2,385)}$ = 1118.80, p = .000. *G1Ma* and *G1Mc* explained *G1Mi* with R^2 = .85. For *G1Ma*, unstandardized β = .30, t = 7.55, p = .000, $r_{partial}$ = .36, r_{part} = .15. For *G1Mc*, unstandardized β = .69, t = 19.19, p = .000, $r_{partial}$ = .70, r_{part} = .38. Mean Creativity was the better predictor of Mean Innovativeness but Mean Aptness played a significant role as well.

Linear regression of *G2Ma* (M_{G2apt} = 4.39, SD_{G2apt} = .69) and *G2Mc* (M_{G2cre} = 4.37, SD_{G2cre} = .65) on *G2Mi* (M_{G2inn} = 4.42, SD_{G2inn} = .65) again revealed that the model was significant: $F_{(2,385)}$ = 948.85, p = .000. *G2Ma* and *G2Mc* explained *G2Mi* with R^2 = .83. For *G2Ma*, unstandardized β = .22, t = 6.76, p = .000, $r_{partial}$ = .33, r_{part} = .14. For *G2Mc*, unstandardized β = .72, t = 21.31, p = .000, $r_{partial}$ = .74, r_{part} = .45.

For Grids1 and Grids2, again, Mean Creativity was the better predictor of Mean Innovativeness but Mean Aptness played a significant role as well.

GLM Repeated Measures (Pillai's Trace) of 7 Sets (between-subjects) of 2 Grids each with 3 Measures (*G1Ma, G1Mc, G1Mi, G2Ma, G2Mc, G2Mi*) (wihin subjects) established the following results (mean values are in Table 1):

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Table 1. Mean values of Aptness (a), Creativity (c), and Innovativeness (i) in Grid1 and Grid2.

	Set	*Mean*	*SD*		Set	*Mean*	*SD*	*n*
G1Ma	1	3.96	.526	*G2Ma*	1	4.12	.64	30
	2	4.38	.63		2	4.28	.87	42
	3	4.29	.91		3	4.44	.97	34
	4	4.03	.81		4	4.36	.74	27
	5	4.29	.36		5	4.35	.34	119
	6	4.21	.74		6	4.16	.84	32
	7	4.48	.67		7	4.64	.69	104
	Total	4.30	.64		Total	4.39	.69	388
G1Mc	1	4.08	.47	*G2Mc*	1	4.09	.59	30
	2	4.41	.64		2	4.46	.78	42
	3	4.21	.84		3	4.37	.89	34
	4	4.08	.72		4	4.39	.79	27
	5	4.27	.38		5	4.32	.40	119
	6	4.30	.80		6	4.24	.85	32
	7	4.50	.59		7	4.50	.62	104
	Total	4.32	.60		Total	4.37	.65	388
G1Mi	1	4.07	.56	*G2Mi*	1	4.07	.69	30
	2	4.47	.62		2	4.54	.69	42
	3	4.28	.87		3	4.42	.92	34
	4	4.08	.66		4	4.35	.72	27
	5	4.30	.33		5	4.39	.37	119
	6	4.19	.85		6	4.24	.84	32
	7	4.56	.60		7	4.58	.63	104
	Total	4.34	.61		Total	4.42	.65	388

Multivariate effects of Grid * Measure * Set were significant: $V = .09$, $F_{(12,762)} = 2.96$, $p = .000$, $\eta_p^2 = .05$. This interaction was supported by Measure * Set ($V = .06$, $F_{(12,762)} = 1.94$, $p = .0.27$, $\eta_p^2 = .03$), by Grid * Set ($V = .04$, $F_{(6,381)} = 2.38$, $p = .028$, $\eta_p^2 = .04$), the main effect of Grid ($V = .04$, $F_{(1,381)} = 14.99$, $p = .000$, $\eta_p^2 = .04$), and the main effect of Set ($F_{(6,381)} = 4.06$, $p = .001$, $\eta_p^2 = .06$). Note that all reported effects had very small effect sizes.

For each Set 1-7, A GLM Repeated Measures (Pillai's Trace) was run for 2 Grid * 3 Measure (within subjects). For Set 1 and Set 6, no effects were significant. For Set 2 ($n = 42$), the multivariate effects of Measure were significant ($V = .19$, $F_{(2,40)} = 4.75$, $p = .014$, $\eta_p^2 = .19$). However, paired-samples *t*-tests among *Set2Ma*, *Set2Mc*, and *Set2Mi* showed no significant differences, according to Bonferroni ($p = .029 > \alpha \approx .017$).

For Set 3 ($n = 34$), the effect of Grid was significant ($V = .15$, $F_{(1,33)} = 5.89$, $p = .021$, $\eta_p^2 = .15$). Paired-samples *t*-tests indicated ($t_{(33)} = -2.21$, $p = .034$, *Cohen's d* = -.38) that Grid2 (Appearance_of) obtained higher scores overall than Grid1 (Capable_of) – this was irrespective of type of Measure.

For Set 4 ($n = 27$), again the effect of Grid was significant ($V = .37$, $F_{(1,26)} = 15.23$, $p = .001$, $\eta_p^2 = .37$). Paired-samples *t*-tests pointed out ($t_{(26)} = -3.90$, $p = .001$, *Cohen's d* = -.75) that independent of Measure, Grid2 (has_Property) obtained higher scores overall than Grid1 (Used_for).

For Set 5 ($n = 119$), the effect of Grid was near-significant with very weak effect size ($V = .032$, $F_{(1,118)} = 3.88$, $p = .051$, $\eta_p^2 = .03$). However, Measure did yield significant effects: *V*

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= .073, $F_{(2,117)}$ = 4.63, p = .012, η_p^2 = .07. Paired-samples t-tests among *Set5Ma*, *Set5Mc*, and *Set5Mi* resulted in a significant difference only for *Set5Mc* vs *Set5Mi* ($t_{(118)}$ = -3.05, p = .003, *Cohen's d* = -.28), the innovativeness being rated higher than the creativity of the examples.

For Set 7 (n = 104), the interaction between Grid and Measure was significant (V = .21, $F_{(2,102)}$ = 13.32, p = .000, η_p^2 = .21), supported by the main effect of Grid (V = .04, $F_{(1,103)}$ = 4.12, p = .045, η_p^2 = .04) and the main effect of Measure (V = .09, $F_{(2,102)}$ = 4.97, p = .009, η_p^2 = .09). The contrast between Grid2 (Part_of) and Grid1 (Has_a) was significant in favor of Grid2 ($t_{(103)}$ = -2.03, p = .045, *Cohen's d* = -.19). For Measure, one comparison was at the conventional cut-off point (p = .05), but corrected for Bonferroni, this result was not beyond doubt. The only significant result was found for *Set7Mc* vs *Set7Mi* ($t_{(103)}$ = -3.08, p = .003, *Cohen's d* = -.30), the innovativeness being rated higher than the creativity of the examples.

Next, across Measures, a Oneway ANOVA (GLM Univariate) was run for the Grids that exerted the strongest effects within their respective Sets (n = 165): Set3_Grid2 (n = 34) vs Set4_Grid2 (n = 27) vs Set7_Grid2 (n = 104). Mean scores are found in Table 2.

Table 2. Mean scores (across all measures) as a function of Grid2 in Set 3, 4, and 7.

Set	Grid		*Mean*	*SD*	*n*
3	2	Appearance_of	4.40	.91	34
4	2	has_Property	4.37	.70	27
7	2	Part_of	4.57	.62	104
Total			4.50	.70	165

Oneway ANOVA of 3 Grids2 with Measure as overall score showed that between-subjects effects of Set were not significant: $F_{(2,162)}$ = 1.37, p = .257, η_p^2 = .02). The differences among the scores to Appearance_of, has_Property, and Part_of were not substantial and these three relations tie for first-place position.

Text analysis

To gain an idea of what participants understood as apt, creative, and innovative, qualitative analysis was performed (cf. Eisenbart, Bouwman, Voorendt, McKillagan, Kuys & Ranscombe, 2022) over the frequencies of occurrence of words and associations mentioned in response to the said variables. The raw results are available in the Supplemental Files. Appendix 2 offers the thematically clustered frequency lists that the analysis is based on. The interpretation uses the word clusters with the highest frequencies of mentioning (*freq.* > 1). Numbers in the text refer to the rank order in Appendix 2.

Aptness was about 1. objects, items, products and their 2. use, which should be 3. fit and 4. functional in line with the 5. user's needs, 6. matching certain attributes and properties with 7. people in their 8. environment, their 9. daily life and use, with enough 11. adaptability, in 12. many ways, for 13. different situations, and for 14. a long time.

Creativity was about 1. innovation, novelty, new things, new functions, new technologies, etc. from 2. ideas that are novel, fresh, special, meaningful, so that 3. things, objects, products transpire from 4. creative 5. ability (e.g., high observation) and possibility of realization, from 7. imagination, and 8. different understanding of things (i.e. refreshing thoughts), a kind of wisdom that brings up 9. unconventional solutions and a degree of breakthrough with 10. good practical applications.

 doi:10.20944/preprints202206.0307.v1

Innovation was a new way of arranging 1. elements, usage scenarios, perspectives, forms, doing discoveries, and having original concepts, novel and interesting thoughts to make 2. new, unprecedented (combinations of) things, original items and objects from 3. ideas that are new, different, and special, showing different thinking directions, which root in 4. creativity and association as well as 6. imagination, a 7. starting point to refresh existing design. In 8. coexisting with humans (i.e. 9. ordinary people), 10. high technology has a 11. different function, on an 12. original basis, and inducing 13. a feeling (a sense) of surprise.

4. Conclusions and Discussion

H1: In line with prevailing theory (e.g., Wang & Hu, 2018), the relationship Similar_to should outdo the other relationships in establishing a creative combination that is deemed innovative and apt. H1 seems to be refuted as GLM Repeated Measures (Pillai's Trace) of 7 Sets of 2 Grids each with 3 Measures (creative, innovative, apt) suggested that none of the measures were sensitive to type of relationship (Grid). Across measures, the best performing relationships were Appearance_of, has_Property, and Part_of, not Similar_to. In the textual data, similarity was mentioned in response to the biomimetic examples in this study. The upshot is, however, that 'similar attribute,' 'similar property,' 'certain similar characteristics' were seen as part of their Aptness while 'similar creative association' was regarded as part of being Innovative (Supplemental Files), not Creativity (!).

H2 counters H1 in saying that it is indifferent which relationship establishes the combination (i.e. H0) as long as that combination is high on creativity, less so on innovativeness and aptness. In stating the Null that it is not necessarily Similar_to that establishes the creative combination, H2 is accepted. However, in the biomimetic examples of the current study, GLM Repeated Measures indicated that their innovativeness was scored as significantly higher than their creativity. Proponents of H1 could now counter that Similar_to can be maintained to establish preeminent examples of creativity rather than of innovativeness. The argument would be that our current examples were exemplifications of innovation rather than of creativity, according to our envisioned end-users, and so Similar_to did not come to the fore that much.

Somewhat in line with this reasoning, note that the bulk of our participants (94%) were Asian (i.e. Chinese) and that McCarthy, Chen, and McNamee (2018) found a so-called 'novelty-usefulness trade-off,' which differs across cultures. These authors state that: "Easterners will perceive a stronger trade-off between novelty and usefulness as compared with their Western counterparts." Maybe this perception evolved from Chinese reforms around the year 2010, which highlighted the practical implications and usefulness of creative endeavors rather than their novelty, as Peng and Plucker (2012) state. Perhaps that in the current research, the strong role of aptness next to creativity pushed up the level of innovativeness of examples and maybe the innovativeness of the examples was deemed higher than their creativity because innovation is more directed at practice and implementation, not merely the ideation stage – as in creativity.

After Beghelli and Jones (2022) and McCarthy, Chen, and McNamee (2018), H3 stated that innovation is creativity that is useful (or 'apt'). Indeed, linear regression showed (i.e. partial and part correlations) that for potential end-users of biomimetic designs Mean Creativity was the better predictor of Mean Innovativeness but that Mean Aptness also played a significant role. This was so for the averages across all biomimetic examples as well as split up into first or second grids.

What did the scores mean? If we take frequency of occurrence as a measure for what comes to mind first when people discuss certain topics, then the focal point of Creativity for our prospective end-users was *new things that transpire from new ideas*. For Innovation, according to our participants, the focus shifted to *new ideas that give rise to new things*. These combined results are a reverse of the common academic idea that ideation (creativity) precedes implementation (innovation).

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Aptness was less oriented on ideas but on *things that are fitting and functional for the user.* The *combination of things* was mentioned under innovation and not under creativity and likewise were notions of similarity mentioned under aptness, not creativity.

4.1. Limitations

Since the large majority of our participants were Chinese, a cultural bias may be insidious in our sample, driving scores more into the direction of practical implications and less so into considerations of creativity. In Ma's (2017, p. 92) study, "...the frequently mentioned "appropriateness" or "value" that emerged in the Chinese context was not mentioned by the UK counterparts." On the other hand, "…the core defining features of creativity, novelty, and appropriateness are shared by people across cultures" (Niu & Kaufman, 2013).

Additionally, maybe not all examples in each grid were of the same quality. As proponents of the similarity-hypothesis may feel, examples that are innovative rather than creative may have drowned out the special role similarity may play in creative combination-making. Nonetheless, the results teach that other relationships than Similar_to also may be candidates for creative combination-making such as Appearance_of (e.g., billboards borrowing the looks of luminous jellyfish), has_Property (e.g., SWAT shield has chameleonic property of cloaking), and Part_of (e.g., elephant trunk as part of a car to wash and wipe the windscreen).

Methodologically, we could have run psychometric scales instead of scores to single items. However, with 3 indicative and 3 counter-indicative items on a scale, 3 measures × 6 items × 50 examples would have resulted into asking 900 scores from each participant, inviting test-fatigue effects. Therefore, I settled for a written response, telling the conceptual meaning in hindsight.

A note on divergent validity

Certainly, hard-nosed psychometrics would emphasize the lack of divergent validity in the scores, leading to exceptionally high correlations among the dependents. And indeed, the bivariate Pearson correlation between Mean Aptness and Mean Creativity was r = .836** (2-tailed); between Mean Creativity and Mean Innovativeness: r = .928** (2-tailed); between Mean Aptness and Mean Innovativeness, r = .844** (2-tailed).

What if I had run psychometric scales, doing Principal Component Analysis (PCA) to sift out 'overlapping' or 'non-discriminating' items? As seen from the textual data, participants merely shift focus between creativity and innovation: either *new things* taking center stage or *new ideas* doing so but *new (things and ideas)* are the most relevant to creativity and innovation as well. In including aptness into the equation, all three variables are about *new things.* By no means does PCA have the sensitivity to detect shifts in foci or discern adjacent, confluent, conceptualizations. PCA wants to see clear distinctions, which are present only in the peripheral (low-frequency) associations to creativity, innovation, and aptness. It would mean that the most important indicators are deleted from measurement. Nevertheless, the partial and part correlations in the regression analysis showed a distinctive 2 to 3 times higher contribution of creativity to innovation as compared to aptness in spite of the high Pearson correlations and 'lack of divergence' among the three dependents. A strong demand on divergent validity would wipe out the central notions of creativity, innovation, and aptness altogether. Or, psychometric scales would be shortened so much that single items would remain but without the textual support.

Reduction of academic theory in practice

Arguably, the Chinese prospective end-users of our biomimetic design ideas had a different conceptualization of what is creative and innovative than academics or design specialists do. For instance, the academic focal point of creativity is similarity between associatively remote entities but participants saw it as an aspect of aptness, the most practical side of design and least related to ideation. On a personal note, in other investigations

of other topics, I often found that the academic sophistication in our models may be analytically defendable but pragmatically mistaken: Non-expert participants do not think the way academics do. For instance, earlier research into the conceptualization of 'creativity' among design students showed that "…the overall indications were that participants could not give a clear and coherent explanation of what creativity was" (Ma, 2017, p. 87). The majority said that creative was novel, appropriate, different from standard items; also something personal, freedom from routine, incremental, common to all, yet others put the conditional that is should be expressed and realized first (Ma, 2017, pp. 90-91).

In other words, we need theoretical models that modulate according to participant stratification. If we are to test very precise theoretical distinctions, then we should test the world view of experts in the discipline. When we ask those questions to non-academics, many of the fine distinctions get blurred and convoluted: They become one and the same concept 'without divergent validity.' All in all, it is questionable to test models of psychology for theoretical reasons against non-expert participants because what will be returned are pragmatics.

4.2. A design method

As to the practical use of the grids we developed in this study, Zheng, Ritter, and Miller (2018) call attention to concept-selection tools and their importance for design education as well as for creative industry and businesses. These authors state that Concept Selection Matrix and Semantic Creativity Assessment Tool help students (and professionals) make design decisions. Particularly early-phase design ideas can be developed during the conceptual design process and evaluated thereafter for, for instance, their value for product design and its development process (ibid.). Business may use such tools to avoid market failure and strongly increase the innovativeness and creativity of their products and services (Zheng, Ritter, & Miller, 2018).

For the master students in design class, making the grids was challenging at first as they had to relate the natural principle to the technology according to a certain relationship (e.g., Desired_by, Symbol_of), which limited free combination making. After a few rounds of trying and testing, however, students acquired a feeling for the type of relationship they wished to convey and then started to develop more and more creative and innovative examples, sometimes more than could be used.

In seeing its quality as a concept-development tool, the biomimetic grids were picked up by my co-teacher, who leads one of the top design companies in Hong Kong. He passed the idea on to Illiza Ho, fashion company, who not only uses the approach to develop novel ideas but also as a concept-selection tool. In that sense, my rating method can quickly show which (variants of) design ideas are preferred by a certain stakeholder group and on what design dimensions, moving above and beyond the biomimetic domain. This may count as the current contribution to "practice-based integrative research" as promoted by Reich (2022).

"So, what is creativity?" Ma (2017) indicates that for most of his participants, the notion was confused. For the prospective end-users of biomimetic designs, creativity is not about similarity between different entities but rather the appearance of the natural phenomenon brought to the new technology, being a part of the new technology, or being a property of that technology. Novelty of things and ideas is seen as creative while innovation is new ideas and new things coming from creativity. Those novelties should be functional and fit the user needs to be regarded as 'apt.'

Acknowledgments: This study was supported by Project P0000254 - *AntiFix: Computational Creativity for Industrial Engineering,* funding scheme: Start-up Fund for New Recruits, grant number 1-BE22. The following students (in no particular order) are kindly acknowledged for creating the biomimetic examples and collecting the data: Jia Wei Zhang, Yi Xin Wang, Rui Ling Fan, Yonglin Dai, Yanyu Wu, Jorge Mejia, Dingyuan Zhang, Xiaomin Guo, Hsueh-cheng Chen, Yiqiao Wang, Baochun Wu, Lin Luo, Chenzi Wang, Jiaming Li, Lili Li, Yiming Wang, Linxin Wang, Jiatong Xu, and Yuming Lu. This study was submitted to the Human Subjects Ethics Application Review and was approved by

the Institutional Review Board, filed under number HSEARS20210923002. The author has no competing interests to declare.

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Appendix 1. Survey biomimetic design ideas (general set-up)

Introduction

You are about to see a grid of 5 pictures in a row and 5 in a column. In combination, they exemplify a certain relationship with each other. We will ask you to score those combinations on aptness, creativity, and innovativeness. It is about your ideas, only later will we ask you what you think being apt, creative, and innovative are about. There is no right or wrong. We are interested in your insights. You will work on two grids with each a different relationship as the topic. Below you see the layout of such a grid.

Relation between the pictures	Picture of a plant or animal	Picture of a plant or animal	Picture of a plant or animal	Picture of a plant or animal	Picture of a plant or animal
Something technological	Natural function put into technology				
Something technological		Natural function put into technology			
Something technological			Natural function put into technology		
Something technological				Natural function put into technology	
Something technological					Natural function put into technology

The first grid: Combined with (here the relationship was stated)

(The description following next differed per grid but the structure was the same)

The first set of examples are protective products designed for use in everyday life with reference to protective solutions found in nature. Peanut and clam have a shell, cabbage has a rind, kangaroo has a pouch, a rose has soft petals, and they all have a function of protecting important cores. We combined these natural functions with a baby's swaddle,

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jewelry box, underwear, mobile-phone case, and a bike helmet. If you have studied the grid, you may click **Next** to proceed to the first combination that you rate for aptness, creativity, and innovativeness.[5]

Relation is: Combined with	Peanuts 	Clams 	Cabbage 	Kangaroo 	Rose 
Baby's swaddle 	The special protection of a peanut shell combined with a swaddle for safekeeping and stabilizing the baby	Half-opened clam shell combined with baby stroller. Can be closed when it rains. Precious as a pearl, the child is in the heart of the parents	Cabbage leaves combined with swaddle: Wrap the child in a series of leaf-shaped covers	Kangaroo pouch combined with swaddle brings the baby closer to the parents, feeling more at ease. Freeing up parents' hands, carrying less weight	Rosebud shape combined with swaddle, a soft wrap with anti-fouling surface
Jewelry box 	Peanut-shape combined with jewelry box creates a double bento box. Inner box keeps the temperature, the outer box is tough, drop-proof, and insulates the heat	Jewelry box combined with shell material. Unauthorized touch will close the shell and protect the pearls	Cabbage leaves combined with jewelry box create a box to store plates as cabbage leaves, saving space and for awesome display	Jewelry box combined with kangaroo makes a self-moving storage bag. With limbs turned, legs and tail serve as supports	Jewelry box combined with a rose. With painful thorns, elegant rosebud design protects precious content against unauthorized access
Underwear 	Peanut combined with underwear creates a textile cushion or pillow with clean-	Clam shell combined with underwear makes a modern version of a chastity belt	Cabbage leaves combined with underwear. Cross-sectional pattern in a variety of	Kangaroo pouch combined with underwear. Panty can be folded over into a washing bag	Rose combined with underwear makes swimming trunks from hydrophobic textiles, anti-bacterial, anti-fouling. With rose-

[5] Phone, courtesy hummingbird, https://morguefile.com/p/526344

Underwear, courtesy TheresaOtero, https://morguefile.com/p/943265

Cabbage, courtesy MGDboston, https://morguefile.com/p/937014

Kangaroo, courtesy anitapeppers, https://morguefile.com/p/842284

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	underwear storage capacity		colors. Multiple layers folded together (i.e. during women's period)		scent after use in swimming pool
Smartphone case 	Peanut with phone case combine into an accessory organizer (e.g., for earphones)	Shell material combined with cell phone makes for a strong, lightweight, environmentally friendly, biodegradable phone case	Cabbage and smartphone combine into a foldable phone case with storage in between leaves	Kangaroo combined with phone case makes a hands-free phone bag carried on the belly	Rose combined with phone case makes a case that automatically folds open when being called
Helmet 	Peanut bike-helmet. Elongated helmet with places for multiple heads: Like a tandem bike, more people wear the same helmet simultaneously	Clam shell combined with helmet. Opens and closes automatically. Can be used as small suitcase	Cabbage leaves combined with helmet is built of removable layers, customizable according to temperature and level of expected danger	Helmet combined with kangaroo creates a helmet that can be carried in front of the belly and be used as a small basket	Different shades of rose colors combined with helmet indicate the level of impact and whether the helmet should be replaced (white, pink, dark red)

(Here, mini-grids drawn from the main grid are presented in random order, different for each participant)

A baby's swaddle combined with a peanut shell

Please rate this combination on aptness, creativity, and innovativeness.

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Relation: Combined with	 **Peanuts**
 **Baby's swaddle**	The special protection of a peanut shell combined with a swaddle for safekeeping and stabilizing the baby

I find the idea to combine the special protection of a peanut shell with a baby swaddle…[6]

apt

Totally disagree Disagree Disagree a little Agree a little Agree Totally agree

1 ------- 2 ------- 3 ------- 4 ------- 5 ------- 6

creative

Totally disagree Disagree Disagree a little Agree a little Agree Totally agree

1 ------- 2 ------- 3 ------- 4 ------- 5 ------- 6

innovative

Totally disagree Disagree Disagree a little Agree a little Agree Totally agree

1 ------- 2 ------- 3 ------- 4 ------- 5 ------- 6

Jewelry box combined with clam shell

Please rate this combination on aptness, creativity, and innovativeness.

[6] Peanuts, courtesy alwaysyoucanstayfit, https://morguefile.com/p/1082956

Baby, courtesy mvelazquez https://morguefile.com/p/907983

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Relation: Combined with	 **Clam**
 **Jewelry box**	Jewelry box combined with shell material. Unauthorized touch will close the shell and protect the pearls

I find the idea to combine a jewelry box with a clam shell for automated protection against thieves…[7]

apt

```
Totally               Disagree  Agree a         Totally
disagree  Disagree  a little  little    Agree     agree

1 ------- 2 ------- 3 ------- 4 ------- 5 ------- 6
```

creative

```
Totally               Disagree  Agree a         Totally
disagree  Disagree  a little  little    Agree     agree

1 ------- 2 ------- 3 ------- 4 ------- 5 ------- 6
```

innovative

```
Totally               Disagree  Agree a         Totally
disagree  Disagree  a little  little    Agree     agree

1 ------- 2 ------- 3 ------- 4 ------- 5 ------- 6
```

[7] Clam, courtesy FreePhotos, https://morguefile.com/p/798518

Box, courtesy anitapeppers https://morguefile.com/p/45692

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A helmet combined with a rose

Please rate this combination on aptness, creativity, and innovativeness.

Relation: Combined with	 **Rose**
 **Helmet**	Different shades of rose colors combined with helmet indicate the level of impact and whether the helmet should be replaced (white, pink, dark red)

I find the idea to combine a helmet with rose colors to indicate damage levels …[8]

Etc.

The second grid: A is a symbol of B

You are halfway. This is the second grid. It shows … (explanations are provided like in the first grid). … If you have studied the grid, you may click **Next** to proceed to the rating of aptness, creativity, and innovativeness.

(Participants rate the mini-grids with Likert-type statements, etc.)

(After finishing the second grid)

Please write no more than 10 sentences on what you think *aptness* is about.

Please write no more than 10 sentences on what you think *creativity* is about.

Please write no more than 10 sentences on what you think being *innovative* is about.

To round off, we ask some questions about you.

54 Gender

1 Male

2 Female

3 Other

[8] Rose, courtesy schurch, https://morguefile.com/p/1025640

Helmet, courtesy click, https://morguefile.com/p/1099272

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55 Age
56 Education
1 Higher
2 Middle
3 Lower

57 Which part of the world are you from?
1 Asia
2 Europe
3 Africa
4 Australia
5 South-America
6 North-America

End of questionnaire. Thank you for your participation.

 doi:10.20944/preprints202206.0307.v1

Appendix 2. Thematically clustered frequency lists in response to Aptness, Creativity, and Innovation
Raw frequencies are available in the Supplemental Files.

Aptness

1. object {occasion}
   things {right}
   items
   products
Mentioned: 48 times

2. use {purpose of, state of, mode of, need of usage}
41 times

3. fit
   suitability {of tools}
32 times

4. function
   functional requirements
19 times

5. need {of user}
18 times

6. match(ing) {degree of}
   similar {attribute, property, certain characteristics}
18 times

7. people {many, group of}
13 times

8. environment {specific economic}
12 times

9. daily {life, use}
   better life
11 times

10. none
10 times

11. adaptability
    phenomenon of adaptation
7 times

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12. many way
3 times

13. different situation
2 times

14. long time
2 times

15. current scene
2 times

16. possible impact {positive, negative}
2 times

17. much mental effort
1 times

18. degree of coordination
1 times

19. terms of temperament
1 times

20. appearance of character
1 times

21. choice of preferences
1 times

22. degree of coherence
1 times

23. law of development
1 times

24. certain characteristics preferences
1 times

25. combination of ideas
1 times

 doi:10.20944/preprints202206.0307.v1

Creativity

1. innovation {technical, application of, creative, pursuit of}
   novelty {creation of}
   new {things, function, original, concept, technology, perspective, field, quantity of,
   quality of, valuable design, basis of}
73 times

2. ideas {new, novel, fresh, special, creative, meaningful}
63 times

3. things
   existing object
   products {combination of}
48 times

4. creative
17 times

5. ability {demonstrated, high observation}
   possibility of realization
17 times

6. none
13 times

7. imagination {foundation of}
12 times

8. understanding of things {appropriate}
   refreshing thought
   different understanding
   kind of wisdom
8 times

9. unconventional solutions
   degree of breakthrough
5 times

10. good practical application
   combination of practicality
3 times

11. foundation of human

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1 times

12. current natural outcomes
1 times

13. term of psychology
1 times

14. field of art
1 times

Innovative

1. innovation {degree of, certain possible}
   innovative, new {way, elements, usage scenario, perspective, discovery, form, era, original concept}
   novel(ty) {thought, interesting}
69 times

2. things {new, old, unprecedented, combination of}
   products {new}
   object, items {original}
50 times

3. ideas {new, different, special, novelty of}
   different thinking directions
43 times

4. creativity {conditions of, similar association}
   case of association
13 times

5. none
9 times

6. imagination
7 times

7. design {existing, refreshing, starting point}
7 times

8. coexistence of human
3 times

9. ordinary people

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2 times

10. high technology
2 times

11. different function
2 times

12. original basis
2 times

13. surprise {feeling of, sense of}
2 times

14. lots of tricks
1 times

15. boundary of humanities
1 times

16. functional technological breakthrough
1 times

17. market acceptance rate
1 times