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ORIGINAL PAPER

Bio-inspired design: the impact of collaboration between engineers and biologists on analogical transfer and ideation

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Abstract

To develop innovative technical solutions, designers seek inspiration from nature and its almost infinite pool of biological solutions. However, understanding biological solutions and transferring appropriate analogies to develop technical solutions pose a considerable challenge. A strategy to facilitate interdisciplinary understanding is collaboration between engineers and biologists. So far, the impact of this type of collaboration on analogical transfer and ideation has not been studied in an experimental setting. To close this research gap, this work examines design experiments with engineer–biologist pairs, half of whom were provided with a support for analogical transfer (*BioId Support*). Engineer–biologist pairs were compared to single disciplinary pairs with regards to the transfer of selected analogy categories. The impact of the transferred analogy categories on the quality of solution ideas was analysed—quality was regarded as an indicator for the solution ideas' innovative potential. The results show a positive influence of the supported collaboration between engineers and biologists on the transferred analogy categories. These analogy categories positively influence the quality of solution ideas. This work indicates benefits of collaboration between engineers and biologists for bio-inspired design. In addition, it provides a starting point for improving bio-inspired design methods.

Keywords Biomimetics · Creativity · Interdisciplinary design teams · Design-by-analogy

1 Introduction

In highly developed economies, innovation is crucial to ensure the survival of companies (Gürtler and Lindemann 2016). A product innovation is the successful implementation of a creative novel idea or invention with a benefit for company and customer (Reichle 2006, p. 20). Consequently, technical product development requires novel solution ideas for the development of innovative products. How can designers in technical companies generate creative novel solution ideas with a high potential for innovation?

One approach is to draw on analogies from distant fields such as biology: Nature offers a large and mostly unexplored pool of biological systems. The solutions which these systems have developed to cope with natural problems and challenges have been tested by millions of years of evolution: biological species either have adapted, optimising their strategies, or they have disappeared (Benyus 2014; Nachtigall 2010, pp. 121–130; VDI 6220 2012).

Bio-inspired design (also called biomimetics, biomimetic design, or biomimicry) is the application of knowledge of biological systems in research and development to solve technical problems and develop technical inventions and innovations (VDI 6220). Stone et al. (2014) emphasize that bio-inspired design aims to "systematically mine biological knowledge to solve existing design problems".

Bio-inspired design is challenging, because it requires expertise in biology and engineering:

As biological solutions can rarely be used in the technical domain directly, bio-inspired design entails a step of abstraction to enable analogical transfer (Lindemann and Gramann 2004; Lenau et al. 2010; Helms et al. 2009). Designers need knowledge in both the biological and the technical domain to master this. However, they commonly only have an educational background in engineering or industrial design, with

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no higher education in biology. Their lack of knowledge in biology complicates bio-inspired design. There is a danger that bio-inspired design "will remain the domain of a few innovators skilled and interested enough to decipher the primary biological literature" (Benyus 2014). To equip engineering students with competences for bio-inspired design, researchers have explored different teaching approaches, such as collaboration in interdisciplinary teams (Goel et al. 2011; Helms et al. 2009) and teaching bio-inspired design using C–K models (Nagel et al. 2017). C–K models make the moves from knowledge acquisition to the development of concepts visible (Hatchuel and Weil 2009).

One characteristic activity in bio-inspired design is the search for biological information. Databases and catalogues provide pre-processed information (e.g., Deldin and Schuknecht 2014; Hill 1997, pp. 107–221; Löffler 2009, pp. 87–95). An example of an online database is www.asknature.org. While catalogues and databases only showcase biological systems that the curators of the catalogue or database have identified as relevant, information on a larger number of biological systems is accessible (e.g. via biological research publications), but biological knowledge is necessary to understand it.

Another characteristic activity of bio-inspired design is the transfer of analogies. Different analogy categories have been proposed in design research (Mak and Shu 2004a, b; Sartori et al. 2010). The formulation of these analogies and the development of solution ideas and concepts again require knowledge in both biology and engineering. Salgueiredo and Hatchuel (2016) emphasize the importance of acquiring additional biological and technical knowledge in parallel to developing bio-inspired concepts. Collaboration between engineers and biologists has been proposed to unite technical and biological expertise (e.g., by Helten et al. 2011; Jordan 2008). Still, few empirical studies have investigated such collaborations (see Sect. 2.3).

The first aim of this work is, therefore, to examine this promising but mostly unexplored approach to bio-inspired design: engineers and biologists collaborating in engineer–biologist pairs to solve a technical task. The focus is bio-inspired ideation in the early phases of product development. During ideation, particularly the second characteristic activity, the transfer of analogies, is crucial. The second aim of this work is, therefore, to evaluate different analogy categories with regards to the solution ideas' potential for innovation.

The work is structured as follows: Sect. 2 gives an overview of the background of this work: the transfer of bio-inspired analogies, the evaluation of solution idea quality, and collaboration between engineers and biologists. Section 3 introduces the research questions and hypotheses. Section 4 explains the experimental approach and Sect. 5 elaborates the analysis of the data. Section 6 shows the results of the analysis. How they relate to other research is illustrated in Sect. 7, with discussion of this paper's limitations in Sect. 8. Finally, Sect. 9 presents a conclusion on the influence of bio-inspired analogies and collaboration between engineers and biologists on solution ideas, as well as an outlook for future work.

2 Background

This section provides an overview of topics relevant to this work: to start with, a characterising element of bio-inspired design is the transfer of analogies from the biological to the technical domain. We, therefore, give an overview on bio-inspired analogies (Sect. 2.1). We start with the process of analogical transfer which has been explored in cognitive psychology. For bio-inspired design, researchers have analysed different analogy categories which we will explore for analysing the outputs of bio-inspired ideation.

To evaluate bio-inspired analogies and the deduced technical solution ideas, their potential for product innovation must be regarded. A product innovation can be defined as the successful implementation of a novel idea or invention with a benefit for company and customer (Reichle 2006). This benefit for company and customer is to a large extent determined by the quality of solution ideas. We will, therefore, use quality measures to evaluate the solution ideas based on bio-inspired analogies. In Sect. 2.2, we deduce quality measures from innovation research.

As explained in the introduction, bio-inspired design and, in particular, the transfer of bio-inspired analogies requires knowledge in biology and engineering. This work looks into the promising strategy of providing this knowledge through collaboration between engineers and biologists. In Sect. 2.3, we, therefore, present existing research on collaboration between engineers and biologists.

2.1 Bio-inspired analogies

Cognitive psychologists have studied the process of analogical transfer and describe it as a knowledge transfer from one familiar situation, the base or source domain, to an unfamiliar situation, the target domain (Gentner 1983; Gick and Holyoak 1983). The mapping between analogues within the source and target domains requires the identification of syntactic, relational properties in particular. According to Hesse (1970), analogies can be distinguished from other types of similarities and comparisons by their purely syntactic rules. Analogues possess "horizontal" relationships between each other and "vertical" relationships between two aspects of the same analogue (Hesse 1970).

Figure 1 shows the adaptation of Hesse's (1970) perspective to bio-inspired design: Examining a problem in the

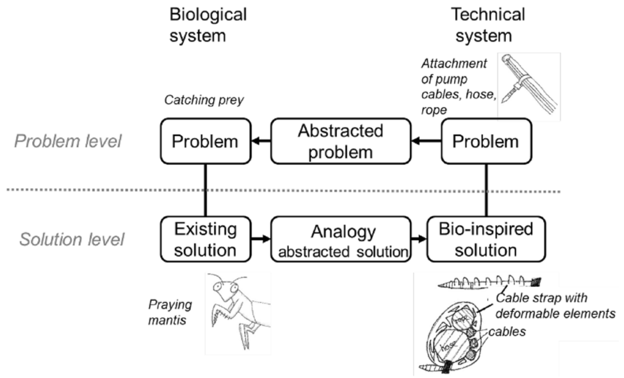


Fig. 1 Analogical transfer in bio-inspired design (based on the perspective of Hesse 1970)

technical domain, a similar problem in the biological domain with an existing solution can be identified via a "horizontal" relationship. The example shown is one of the technical tasks used in this work—the attachment of cables, hose, and rope of *a* pump and a possible inspiration, the biological system *praying mantis*. The praying mantis grabs its prey with its legs, which are equipped with spikes. The "vertical" problem—solution relation in biology can be transferred to the technical domain for the development of a bio-inspired solution. For example, the bio-inspired solution can use an abstracted version of spikes—deformable elements that clamp the cables.

As Fig. 1 shows, bio-inspired design usually implies two steps of abstraction (abstraction of the technical problem and abstraction of the biological solution). In addition, the resulting bio-inspired solution is, in most cases, not the same as the existing biological solution. Based on this finding, researchers have developed analogy categories to differentiate between various abstraction and difference levels:

Mak and Shu (2004b) and Vakili et al. (2007) use four categories to evaluate the **accuracy** of bio-inspired physical effects and working principles ("strategies"): *Unrelated* strategies have no link to the biological system. *Incorrect* strategies are inspired by the biological system, but the designers misinterpret the biological strategy. *Incomplete* strategies adopt a "general principle" of the biological strategy, but they do not apply the concrete strategy (Vakili et al. 2007). *Correct* strategies use "similar elements" as the biological strategy (Mak and Shu 2004b).

Mak and Shu (2004a) evaluate **similarity** using two dimensions: The "strategic accuracy" and the "abstraction of biological entities": An analogy is evaluated as "strategically accurate" if the biological strategy to solve the addressed problem is transferred to the technical solution idea. The biological entities are considered "abstracted" if the biological system or parts of it are not part of the technical solution idea. Using the two dimensions, four categories are defined [strategically accurate: *analogy* (abstracted), *literal implementation* (not abstracted); not strategically accurate: *anomaly* (abstracted), and *biological transfer* (not abstracted)].

Sartori et al. (2010) analysed analogies using the *SAPPhIRE* model (Chakrabarti et al. 2005) and identified five abstraction levels, on which bio-inspired analogies are transferred—the **elements of transfer**: *Copy parts* express the use of the biological material and structure for the technical solution. *Transfer organs* denote the transfer of properties or conditions that are necessary for solving the problem. *Transfer attributes* imply the transfer of properties which cannot be unambiguously linked to the addressed problem. An abstract analogical transfer is entailed by *transfer state change*, i.e., the technical system solves a similar problem as the biological system, but not with the same means. "Resulting transfer" describes an unintended transfer of analogies or similarities from the biological system.

In this work, we will analyse the outputs of bio-inspired ideation with regards to these analogy categories (accuracy, similarity, and elements of transfer). The details are described in the section on analysis methodology (Sect. 5).

2.2 Quality of solution ideas as an indicator for innovation potential

In bio-inspired ideation, analogies serve to develop solution ideas in the early phases of the product development process. During the subsequent stages of the product development process, innovative products have to be developed based on these solution ideas. According to Reichle (2006, p. 20), a product innovation is the successful implementation of a creative novel idea or invention with a benefit for company and customer. To provide this benefit, innovative products must be successfully sold on the market. In technical product development, a common approach to achieve this market success is the definition and tracking of the solution's quality using customer and company requirements. (Lindemann 2009, pp. 84–85; Pahl et al. 2007, pp. 213–215; DIN 2005).

To evaluate the quality of solution ideas in the early phases of the product development process, researchers have adapted this approach to the preliminary character of solution ideas: numerous aspects of the technical solution have not yet been determined; therefore, an evaluation in regard to detailed requirements is challenging (Lindemann 2009, pp. 180–181). The proposed quality criteria can be categorised as task-independent and task-specific:

A task-independent, general aspect is feasibility: Under the headline *feasibility*, we can summarise criteria such as manufacturability, effort of implementation, estimated costs, etc. (Messerle et al. 2013; Shah and Vargas-Hernandez 2003; Reinig and Briggs 2008) Task-specific requirements can be deduced from the crucial requirements or the unique selling point of the product to be developed. If prototypes are built, even technical performance can be measured (Shah and Vargas-Hernandez 2003).

In this work, we will consider the task-independent quality criterion feasibility and several task-specific quality criteria. We describe the details in the section on analysis methodology (Sect. 5).

2.3 Collaboration between mechanical engineers and biologists

A number of researchers (e.g., Vattam et al. 2008, 2009, 2010; Helms et al. 2009; Helten et al. 2011) have studied collaborations between mechanical engineers and biologists. They observed teams of undergraduate students of biology and engineering. The teams worked on an entire engineering design process over an extended period of time. Overall, they could report positive results: for example, Helten et al. (2011) observed that the collaboration entailed a better and quicker understanding and evaluation of biological systems. On the downside, they found that knowledge transfer between engineers and biologists can be hindered by different presentation of information and different terminology (Helten et al. 2011; Jordan 2008, p. 107).

The studies' explanatory power is limited by three factors: First, the teams consisted of undergraduate students, i.e., novices in their disciplines. Therefore, the results can only be transferred to collaborations between graduate, experienced mechanical engineers, and biologists with limitations. Second, as long-term projects were observed, not every design stage was studied in detail and there are no specific results on ideation activities. Third, the studies did not compare engineer–biologist teams to single disciplinary teams of biologists or mechanical engineers. Consequently, an evaluation of the effect of the bi-disciplinarity of the teams is not possible.

One aim of this work is, therefore, to address these gaps and to study collaborations of graduated biologists and mechanical engineers in an experimental setting in which the details of bio-inspired analogical transfer can be observed.

3 Research questions

In bio-inspired design research, different analogy categories have been defined and analysed (e.g., by Mak and Shu 2004a, b; Sartori et al. 2010). Their impact on the quality of solution ideas has not been researched except for the accuracy of analogies (Cheong et al. 2010). This is the aim of the first research question of this work. As we will explain in Sect. 5.3, we will assess the influence of selected analogy categories which transfer a biological strategy without transferring the biological embodiment, i.e., *correct* and *incomplete* analogies (accuracy), *analogies* (similarity) and *organ* and *state change* (elements of transfer). We will compare solution ideas containing these selected analogy categories to other solution ideas with regards to task-specific quality criteria and feasibility. We expect a positive influence on task-specific quality criteria. However, we do not expect a positive influence on feasibility criteria, such as manufacturability and effort of implementation, because we expect bio-inspired solution ideas to differ more from the existing technical products than the solution ideas not inspired by biology. Consequently, we expect bio-inspired solution ideas to require more efforts for implementation. We formulate the research question and the hypotheses, therefore, as:

1. How do the analogy categories *accuracy, similarity,* and *elements of transfer* influence the quality of solution ideas?

Hypotheses:

Solution ideas containing *correct* and *incomplete* analogies (accuracy), *analogies* (similarity), and *organ* and *state change* (elements of transfer) have a higher task-specific quality Q than

1. solution ideas not inspired by biology and
2. bio-inspired solution ideas containing other analogy types.

In a second step, the influence of biologists and engineers on the transfer of bio-inspired analogies is assessed. As shown in Sect. 2.3, collaboration of graduated engineers and biologists in the ideation phase has not been researched in an experimental setting. An experimental setting allows to analyse the transfer of analogies and the development of solution ideas in detail (e.g., by analysing videos and transcription of the ideation). In this work, we will analyse the influence of collaboration between engineers and biologists on the selected analogy categories in an experimental setting. As collaborations between engineers and biologists face challenges due to different manners of presenting information, we will develop the *BioID Support* to mitigate the differences (depicted in Fig. 5). This support will be given to half of the engineer–biologist pairs (referred to as *support pairs*). We expect that the engineer–biologist and the support pairs profit from their knowledge of biology and mechanical engineering and transfer a higher proportion of the selected analogy categories than the single disciplinary pairs.

The second research question and the hypotheses are, therefore, formulated as:

2. How does supported collaboration between engineers and biologists influence the analogy category?

Hypotheses:

1. Engineer–biologist pairs
2. Support pairs

transfer/document a higher proportion of the selected analogy types than single disciplinary pairs.

The following sections explain the experimental methodology (Sect. 4) and analysis methodology (Sect. 5).

4 Experimental methodology

To answer the research questions, design experiments were conducted with pairs of biologists and engineers working on an ideation task. This subsection provides the information on the participants, the experimental procedure, and the materials.

4.1 Participants

For this work, design experiments with ten biologists (four of whom had graduated in biophysics, biochemistry, bioinformatics, or biogeography) and ten mechanical engineers were conducted. The participants were research assistants at several laboratories working in different areas of biology and mechanical engineering. Each participant worked on a doctoral thesis in a different area of study. A list of the research topics of the participants can be seen in the additional material (1.1). They volunteered for participation in the experimental study. The participants had no experience in bio-inspired design.

4.2 Experimental procedure

Figure 2 illustrates the experimental procedure: It consists of two design experiments per participant, questionnaires and individual tasks.

Taking into account the availability of the participants, two biologists (termed biologist *x* and *y* in Fig. 2) and two engineers (termed engineer *x* and *y* in Fig. 2) were assembled. Each design experiment was conducted with a pair of two participants:

- Each participant first collaborated with another participant from the same discipline working on one design task (single disciplinary biologist or engineer pair).
- In the second design experiment, each participant collaborated with one participant from the other discipline working on a different design task (engineer–biologist pair). These pairs were formed by lot. Half of the engineer–biologist pairs worked with the *BioId Support* (support pairs).

The participation in an unsupported engineer–biologist pair or support pair depended on the date of the experiment, as the *BioId Support* was developed based on a preliminary analysis of the first experiments. In total, there were five pairs of each condition: biologist pairs, engineer pairs, engineer–biologist pairs (without support), and support pairs.

The participants received an individual task before the design experiments, as well as after the ideation in single disciplinary pairs and after the ideation in engineer–biologist pairs, to control for order effects due to learning or fatigue. After both ideation tasks, the participants had to answer a questionnaire with questions on each ideation. The analysis of the questionnaires did not provide relevant results for this work's research questions and is, therefore, not included here (for more details see Hashemi Farzaneh 2016).

4.2.1 Materials

The following paragraphs explain the materials given to the participants, i.e., the material for the ideation in pairs, the *BioId Support,* and the individual task.

4.2.1.1 Tasks, biological information, and documentation material All pairs received a design task. It consisted of a textual description, in two cases an illustrative figure, and the task itself. The task was described by a sentence of the form "develop a solution to …" The instructions required

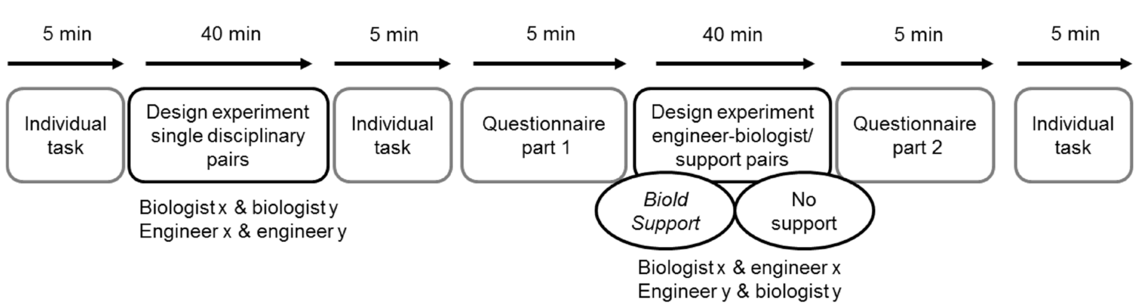


Fig. 2 Experimental procedure

the development of as many solutions as possible and their documentation in annotated sketches. Two or three requirements were given.

The participants were neither given instructions on bio-inspired design nor told to develop bio-inspired solution ideas. They received a video, a Wikipedia article and a research publication under the headline "information from biology". The different sources of information were meant to replicate realistic sources of information in bio-inspired design and creative ideation in general. In addition, they varied with regards to the amount of textual vs. pictorial information: The research publications included mostly textual information; the selected videos included mostly pictorial information (they included none or only superficial comments). The Wikipedia article included both text and pictures. The influence of textual vs. pictorial information on analogical transfer has been analysed in several studies, but there is no clear recommendation whether text or pictures should be preferred (Gonçalves 2016).

Three different comparable design tasks and selected biological information for each task (video, Wikipedia article and research publication) were used. The tasks were (1) to develop a device which attaches cables, hose, and rope of a water pump to each other, (2) to develop sun protection for buildings, and (3) to reduce aquaplaning of automotive vehicles. Details on the task *"Attachment of Water Pump"* (task 1) are shown in Fig. 3. Details on the other tasks can be taken from the additional material (1.2). The participants received paper and pens to document their ideas. The support pairs (engineer–biologist pairs working with a supporting tool) were additionally given the *BioId Support, as* described in the next paragraph.

4.2.1.2 BioId support A preliminary analysis of the first experiments showed that on average, engineer–biologist pairs performed better in terms of analogical transfer, but there was no statistical significance. Comparing the sketches of engineers and biologists, we observed differences in dealing with the biological information. The engineers tended to focus on technical solutions and to neglect a detailed analysis of the biological models. The biologists rather analysed the biological models in detail, but did not develop concrete technical solutions. For example, Fig. 4 shows solutions to the task "Attachment of water pump" documented by an engineer and a biologist. Both base their solutions on an analogy from the Wikipedia article on byssus (see Fig. 3):

- The engineer determines three possible locations to use "byssus" to provide a friction force to hold the cables together: (a) cable strap, (b) cables, and (c) hull around cables (solution-focus).
- The biologist does not propose a concrete solution, but poses a question on the feasibility of using an imitation of byssus (analysis of biological model) and suggests a vague idea for actuation.

As reported by Jordan (2008), this discipline-specific use and presentation of information can hinder collaboration between engineers and biologists (see Sect. 2.3). We developed the *BioId Support* (***Bio****-inspired* ***Id****eation Support*) to support engineer–biologist pairs by providing a discipline-spanning manner of presenting information. It guides both engineers and biologists through a common process of analysis and analogical transfer.

From the preliminary analysis, we deduced four concrete requirements, namely (1) implementation of a structured

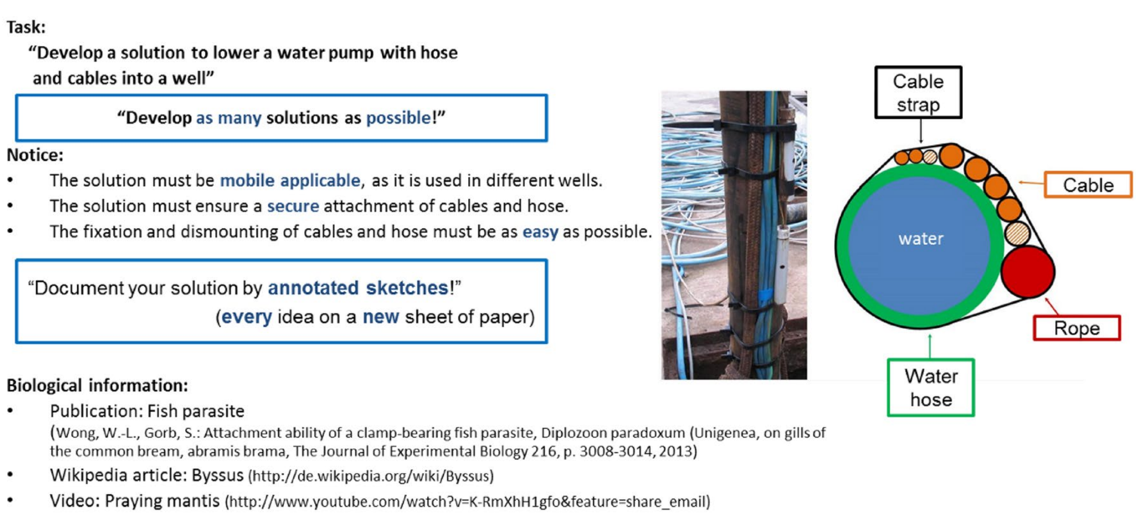


Fig. 3 Design task "Attachment of Water Pump" (an additional text describes the challenges: attaching cables, rope, and water hose to each other so that they do not slip; the risk of injury for dismounting should be reduced in comparison to cable straps)

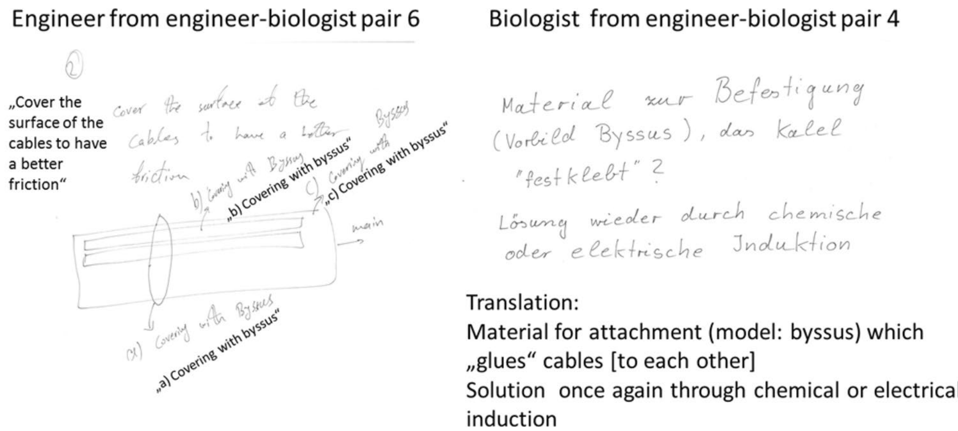


Fig. 4 Example of engineer- and biologist-specific presentation of information—solutions to the design task "Attachment of water pump"

procedure (analysis of the technical/biological system, transfer analogy, and document bio-inspired solution), (2) discussion of the technical task, (3) support of sketching, and (4) transfer of several analogies based on one biological system (as proposed by Shu and Cheong 2014; Nagel et al. 2015).

To conceptualise the *BioId Support*, two existing supports for bio-inspired design were analysed in detail: The *Inspiration* or *BioCard* approach (Lenau et al. 2010, 2011, 2015) and the *KoMBi* approach (Hashemi Farzaneh et al. 2015). The *BioCard* approach focusses on preparing information for analogical transfer, and the *KoMBi* approach focusses on combining aspects from biology-specific and engineer-specific models to a common modelling approach. On the low abstraction level of the biological or technical system embodiments, sketching is used by both approaches. On the high abstraction level of working principles and functions, the *BioCard* approach focuses on textual descriptions, whereas the *KoMBi* approach uses graph representations.

A concept for the *BioId Support* was developed, tested, and then improved. It combines aspects from the *BioCard* and the *KoMBi* approach supporting the participants to use sketching and graph representation. The result is shown in Fig. 5.

To implement a structured procedure (requirement 1), the *BioId Support* consists of one template for discussion of the technical task (requirement 2) and one template for each biological information source (video, Wikipedia article, and research publication). The templates for each information source are used to discuss the biological information and to directly transfer analogies and generate solution ideas. To support sketching (requirement 3), they request sketches and graph representation adapted from the *BioCard* and *KoMBi*

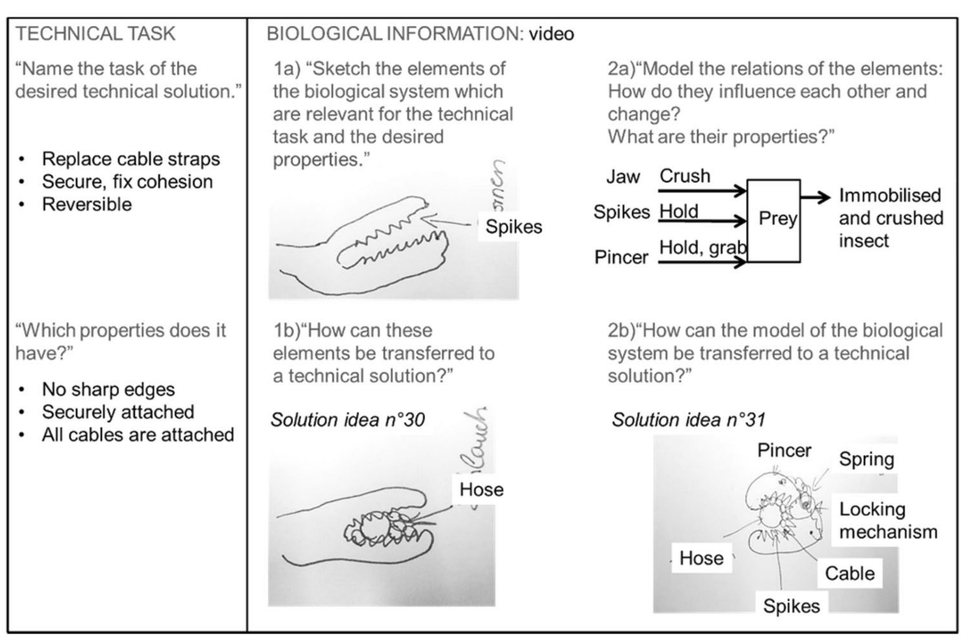


Fig. 5 Translated example of the use of the *BioId Support* (the template is in grey; the pair's input in black script)

approaches. Sketching has been proposed to facilitate the transfer of bio-inspired analogies (Weidner et al. 2018).

To foster the transfer of several analogies (requirement 4), a two-step approach is adopted in analogy to the *BioCard* and *KoMBi* approaches: The participants are requested to discuss the biological information on a low abstraction level and to describe their elements (see Fig. 5, 1a). Based on this description, they are asked to transfer a solution via a first analogy (1b). For the second step, the participants are requested to abstract the biological system and to represent the relations between its elements (2a). They are asked to transfer a solution via a second analogy based on this representation (2b). The complete *BioId Support* is shown in the additional material (1.10).

Figure 5 shows an example of the use of the *BioId Support* from one of the design experiments. Here, the technical task is the *attachment of water pump* (with cables, rope, and hose). The video for this task is about a praying mantis.

On the video template, the pair sketched the praying mantis' clamp with its spikes. The pair transferred an analogy based on this sketch. As Fig. 5 shows, the sketch of the solution idea resembles the praying mantis: a hose is fixed by spikes of a clamp. In a second step, the pair modelled the functions of several of the praying mantis body parts, the *pincer holds* or *grabs the prey*. Based on this model, the pair completed the solution idea with a spring that actuates a locking mechanism. This additional analogy is more abstract, because it only shares the abstracted function *hold* with the biological system.

4.3 Individual tasks

Three individual tasks were used to test possible order effects due to fatigue or learning from the design experiments. As shown in Fig. 2, each participant had to do one individual task before the design experiments (pre-test), one after the participation in a single disciplinary pair (post-test 1) and one after the participation in an engineer–biologist pair (post-test 2). By this means, each participant's improvement due to learning or decreasing performance due to fatigue throughout the design experiments was monitored.

Each task consisted of two parts:

- Part 1: Which aspects of (a given biological system) are interesting for a technical application?
- Part 2: Which aspects of (a given technical system) could be improved by bio-inspired design? Name a possible biological inspiration!

The two parts were chosen to resemble (1) a problem-driven (or biology push approach) and (2) a solution-driven (or technology pull approach). These two approaches have been postulated as opposite procedures with their specific challenges, as (1) starts with an analysis of the biological solution and (2) starts with an analysis of the technical problem (Helms et al. 2009; VDI 6220). We assume that the ability of a participant to follow both procedures shows their general ability in bio-inspired design.

Three different biological and technical systems were given in varied order: elephant and ship, dolphin and robot, and bat and aeroplane. The participants were given a table for each part of the task with columns for the aspects of the biological/technical systems and the designated technical/biological system. The two parts of the individual tasks were done consecutively with 5 min allocated to each.

5 Analysis methodology

The analysis of the design experiments began with the coding of the design experiment videos and identification of each solution idea (Sects. 5.1, 5.2). This approach detaches the solution ideas from the individual pairs and enables a coherent and objective analysis. In a next step (Sects. 5.3, 5.4), we analysed the solution ideas regarding analogy categories and quality (research question 1). The results were mirrored to evaluate the pairs and to evaluate the influence of the *BioId Support* (research question 2). Finally, measures for the verification of the results were taken (Sect. 5.5).

5.1 Coding of the design experiments

At the end of the experiment, the design task, the printed research publication, the paper sheets, and, in case of a support pair, the templates of the *BioId Support* were collected. Notes and documented solution ideas were identified on the collected documents. Examples of documented solution ideas can be seen in Fig. 5 (solution ideas n° 30 and 31). In addition to the documented solution ideas (text or sketches), undocumented solution ideas (only verbal communication) were identified on the videos of the design experiments. In the analysis, we considered these categories separately, because in a real setting of an ideation workshop, most solution ideas which are not documented are not further developed. Our observation in the previous design experiments was that many potentially good solution ideas remain undocumented. We, therefore, analyse all generated solution ideas (documented and undocumented) and documented solution ideas separately.

To analyse the videos, a coding scheme based on previous work was used (Hashemi Farzaneh et al. 2012). A list of all solution ideas and the sketches of the documented solution ideas are included in the additional material (1.4 and 1.5). The following codes are relevant to this work:

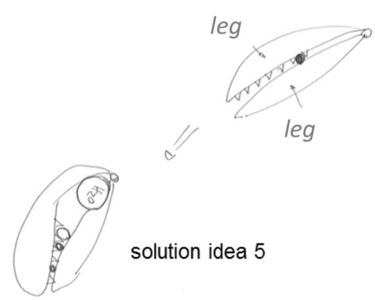
- Biological information and knowledge: discussing publication/Wikipedia article/video/further biological knowledge
- Analogical transfer: relating biological information and knowledge to the task
- Solution idea: The generation of a new solution idea is indicated by:
    - New category: generating a solution idea of another semantic category than the previous solution idea (e.g., based on another biological inspiration)
    - Expansion of the scope: generalising or abstracting a solution idea
    - Variation: generating a solution idea which is semantically related to the previous one, but aspects of the idea are changed

No new solution idea is indicated by:

- Concretisation: detailing a solution idea
- Repetition: repeating a previously generated solution idea without changes

An example of the use of the coding scheme is shown in Table 1: It lists part of the transcribed communication from one of the design experiments (biologist pair 1) and the assignment of the communication to codes. This excerpt includes the generation of two solution ideas, which can be identified by the codes "solution idea: new category" (time: 22:50) and "solution idea: variation" (time: 23:40). Before coming up with the solution ideas, one of the participants speaks about the praying mantis demonstrated in the video. An analogical transfer can be identified ("It has these spikes, that means…" [switching to the technical solution idea]) and, therefore, both

Table 1 Excerpt of the verbal communication (translation) from the ideation in biologist pair 1 and identification of the codes (b1 and b2: participating biologists)

Time [min:s]	Communication	Code	Identified solution idea
22:30	b1: If you look at the leg of the praying mantis, it has…	Biological information: video	
22:40	b1: …well it sometimes closes its arms like this. [sketching] It has these spikes; that means…	Biological information: video; analogical transfer	
22:50	b1: …you could also have the hose here. Then you would have—let's do this here:	Solution idea: new category	Solution idea n°5 (clamp with spikes)
23:00	b1: [sketching]		
23:10	b1: Then you would have something with a joint and a big gap…	Solution idea: concretization	
23:20	b1: …it's not quite like this… then here is the water hose… b2: yes	Solution idea: concretization	
23:30	b1: …then you would have gaps of different sizes for the small hoses*	Solution idea: concretization	
23:40	b2: You can also do something like a cable strap, but with spikes. Spikes that can be shifted.	Solution idea: variation	Solution idea n°6 (cable strap with shiftable spikes) 
23:50	b2: According to the distance between the spikes, there is more space for the hose. Also for hoses of different sizes*	Solution idea: concretization	

*The task is to attach a hose and several cables of different diameters to the rope that holds the water pump. The two participants refer to the cables with the term "small hoses" solution ideas are considered to be based on a bio-inspired analogy from the video.

5.2 Categorisation of solution ideas

In a next step, the solution ideas for each of the three tasks were analysed and compared. In this work, "solution idea" is defined as a communicated thought that proposes a (partial) fulfilment of a given design task (based on Feldhusen and Grote 2013; Lindemann 2009). Solution ideas that do not fulfil a portion of the task or only specify a function were excluded from further analysis.

The solution ideas were analysed on four abstraction levels (definitions based on Ponn and Lindemann 2011, pp. 427–460):

- Function: the purpose of a technical solution (idea) and its elements
- Physical effect: physical law that supports the function
- Working principle: combination of geometric and material properties that enable the physical effect
- Embodiment: detailed design of the components of a technical solution (idea)

On embodiment level, all solution ideas were different. However, on the more abstract levels, similar working principles, physical effects, and functions could be identified. Each solution idea implements one or several working principles, physical effects, and functions. Complete lists of solution ideas on embodiment level and on working principle level (assigned to physical effects and functions) are shown in the additional material (1.5).

As an example, the assignment of the solution ideas extracted from the discussed communication excerpt (see Table 1) to working principles, physical effects, and functions is shown in Table 5. It can be seen that both solution ideas present a solution to the function *hold* and *adapt to the diameter of cables/hose*. Solution idea n°5 adapts to different diameters in discrete steps, i.e., the spikes are fixed, whereas solution idea n°6 allows for continuous adaptation with shiftable spikes. In addition, solution idea n°6 provides a solution to the function *tighten*. For solution idea n°5, the participants did not define a tightening mechanism for the clamp (such as a spring, a snapping mechanism, etc.).

This example shows that the approach to partition the solution ideas with regards to working principles, physical effects, and functions allows a coherent comparison between them. Comparing solution ideas n° 5 and 6, for example, shows that both ideas include similar physical effects. The comparison additionally shows that solution idea n° 6 presents a more complete solution to the task, because it addresses the function "tighten".

5.3 Analogy categories

Bio-inspired analogies can be identified in the participants' communication: When participants discussed biological information, this was frequently followed by the development of an analogy-based solution idea. The analogy is, therefore, inseparable from the solution idea, making it merely a theoretical concept. This becomes evident in the following communication excerpt: One participant says about the praying mantis: "It has these spikes [biological information], **that means** you could also have the hose here [solution idea]." In this case, the connection of biological information and a new solution idea through the term "that means" indicates the analogy.

Using videos and transcription, the analogies were, therefore, associated with preceding communication of information or knowledge. If the communication was related to the publication, Wikipedia article, video, or further biological knowledge, the analogies were considered "bio-inspired". There were also analogies based on other knowledge, e.g., knowledge about existing products: In this work, these analogies were ignored.

The three definitions explained in Sect. 2.1 are used to analyse the analogy category of the bio-inspired solution ideas: *accuracy* (Mak and Shu 2004b; Vakili et al. 2007), *similarity* (Mak and Shu 2004a), and *elements of transfer* (Sartori et al. 2010). Table 2 shows the interpretation of these variables in this work. As the descriptions of the analogy categories show, the concepts of *accuracy*, *similarity,* and *elements of transfer* are related. Solution ideas can be sorted into several categories. For example, the previously discussed solution idea n° 5 (see Table 5) includes the solution idea "spikes" on working principle level. These "spikes" are similar to the spikes of a praying mantis with respect to working principle, physical effect (form closure), and function (adaptation to different diameters of cables/object size). The analogical transfer of the "spikes" is, therefore, categorised as *correct* (accuracy), an *analogy* (similarity), and being a transfer of *organs* (elements of transfer).

For the quality analysis, the focus was on the categories of accuracy, similarity, and elements of transfer that transfer the function of the biological system and not necessarily the embodiment. As Table 2 shows, these are the categories of *correct* and *incomplete* analogies (accuracy), *analogies* (similarity), and *organ* and *state change transfer* (elements of transfer). They are printed bold in Table 2.

A reason for this is given by Mak and Shu (2004a):

> "However, the potential of biomimetic design is fully realized when one can abstract a strategy used in biological phenomena and implement this strategy in a way that is not limited to a literal one using the same biological players."

Table 2 Measures for the analogy category (measured on solution idea level)—the selected analogy categories are printed in bold

Variable	Values	Comparison to the biological inspiration (x: different, o:different or similar, ✓: similar)			
		Embodiment	Working principle	Physical effect	Function
Accuracy based on Mak and Shu (2004b) and Vakili et al. (2007)	Unrelated	x	x	x	x
	Incorrect	o	✓	x	o
	Incomplete	x	x	x	✓
	Correct	o	o	✓	✓
Similarity based on Mak and Shu (2004a)	Biological transfer	✓	✓	x	x
	Literal implementation	✓	✓	✓	✓
	Analogy	x	o	o	✓
	Anomaly*	x	o	x	o
Elements of transfer based on Sartori et al. (2010)	Copy parts	✓	✓	o	o
	Transfer organs	x	o	✓	✓
	Transfer attributes	x	✓	x	o
	Transfer state change	x	x	x	✓
	No transfer	x	x	x	x

*Anomaly: transfer of either working principle OR function (or no transfer)

For example, Nagel et al. (2015) analysed inexperienced designers (undergraduate students) and found that they mostly transferred embodiments and had difficulties in transferring analogies on function or system property level.

In this sense, it is assumed that transferring the function without a focus on the embodiment in the biological system implies an understanding of both the biological system and the technical task. This is in accordance with Gentner's (1983) view that two analogues must be similar with regards to structure, but they are not necessarily surface similar. Other analogy categories, for example those based on misunderstanding of the biological information, can still result in solution ideas with high quality, but are random and, therefore, less reproducible.

5.4 Quality

As discussed in Sect. 2.2, quality can be measured by general feasibility criteria and task-specific criteria.

In this work, the probability that the solution idea can be developed into a solution or product is estimated as the *feasibility* of a solution idea.

Task-specific quality criteria are defined based on the design tasks and (partial) functions. They are exemplarily listed in Table 3 for the task *"Attachment of Water Pump"*. For the other two tasks the criteria are listed in the additional material (1.6). The overall value for each solution idea on embodiment level is calculated using the weighting factor w (see Table 3 and additional material 1.6).

The criteria are rated with values ranging from 0 to 3 corresponding to 0…100%. The assignment of values is defined as shown in Table 4. This coarse rating scale is chosen because of findings by Kurtoglu et al. (2009) and Linsey et al. (2012), which show that broader scales with undefined interim values can cause differences between evaluators.

The overall value for feasibility of a solution idea F on embodiment level is rated as the minimum value f of all contained working principles. This is due to the fact that if one of its working principles is not feasible, the whole solution idea cannot be applied in reality:

Table 3 Task-specific quality criteria for the task "Attachment of Water Pump"

Function	Task-specific quality criteria q	Weighting factor w
Hold	Attachment in wet state	0.33
Adapt to diameter of cables/hose (discrete steps/continuously)	Attachment of cables with different diameters	0.33
Tighten, loosen, tighten, and loosen, lower pump into well	Easy assembly (quick, no specific knowledge or tools required, no risk of injury)	0.17
	Reusability	0.17

Table 4 Evaluation of feasibility and task-specific quality criteria using points 0–3

Value	Task-specific criteria *q*	Feasibility *f*
3 (100%)	Criterion fulfilled for all application cases	Material/components available, costs probably within the expected margins, integration to predefined system(s) possible
2 (66%)	Criterion fulfilled with reservations: not for all application cases/ criterion less well fulfilled	Material/components available, but high costs or: existing system(s) have to be replaced/adapted
1 (33%)	Unclear if the criterion can be fulfilled or: solution has undesired properties	Material/components not completely defined, unclear if the material/components can be obtained (because they are not commercially available)
0	Criterion not fulfilled or: solution not aimed at the function fulfilling the criterion	Not feasible

Table 5 Example for the evaluation of solution ideas

Solution idea	Working principle	Physical effect	Function	Analogy categories	Quality		
					f	Addressed task-specific quality criterion	*q*
Solution idea n°5 (clamp with spikes)	Clamp	Static friction	Hold	Correct, analogy, transfer organs	3	Attachment in wet state	2
	Spikes between cables/hose/rope	Form closure	Adapt to diameter of cables/ hose (discrete steps)	Correct, analogy, transfer organs	3	Attachment of cables (different diameters)	2
	Overall feasibility $F=3$ (Eq. 1) Overall task-specific quality $Q = \frac{2 \cdot 0,33}{3} + \frac{2 \cdot 0,33}{3} = 44\%$ (Eq. 2)						
Solution idea n°6 (cable strap with shiftable spikes)	Wrap	Static friction	Hold	Unrelated anomaly	3	Attachment in wet state	2
	Cable strap	Form closure	Tighten	Unrelated anomaly	3	Easy assembly Reusability	0 0
	Shiftable spikes between cables/hose/ rope	Form closure	Adapt to diameter of cables/ hose (continuously)	Incomplete, analogy, attributes	3	Attachment of cables (different diameters)	3
	Overall feasibility $F=3$ (Eq. 1) Overall task-specific quality $Q = \frac{2 \cdot 0,33}{3} + 2 \cdot \frac{0 \cdot 0,17}{3} + \frac{3 \cdot 0,33}{3} = 55\%$ (Eq. 2)						

$$F = \min\{f_1 \dots f_n\} \text{ with } n = \text{all working principles of the solution idea.} \tag{1}$$

To calculate an overall value Q for the task-specific quality of a solution idea on the embodiment level, all working principle values q are summed up, multiplied by the weighting factor w (see Table 3) and divided by three, the maximum possible value:

$$Q = \sum_{i=1}^{n} \frac{q_i \cdot w_i}{3} \text{ with } n = \text{all working principles of the solution idea.} \tag{2}$$

Table 5 shows the evaluation of the two discussed solution ideas for the task *"Attachment of Water Pump"* (see Table 1). Both solution ideas are rated with the maximum feasibility value $F=3$, since their components are available at low cost and they can be integrated to the predefined system of the water pump.

Regarding task-specific quality, both solutions are rated with the value $q = 2$ for the criterion “attachment in wet state”. Both solutions can attach the cables, hose, and rope, but neither the clamp (solution n° 5) nor the “wrap” of the cable strap (solution n° 6) prevents the slipping of wet cables with a small diameter. For the criterion “attachment of cables with different diameters“, the evaluation differs: The shiftable spikes of solution idea n° 6 can be adapted to differing cable diameters flexibly, whereas the fixed spikes of solution idea n° 5 only provide space for predefined cable diameters. Therefore, the shiftable spikes are rated with the value $q = 3$, the fixed spikes with the value $q = 2$. As Table 5 shows, solution idea n° 6 (cable strap) addresses two more task-specific criteria than solution idea n° 5, namely *easy assembly* and *reusability*. However, these criteria are rated with zero points, as a cable strap provides a high risk of injury during the assembly process and is not reusable. The evaluation of task-specific criteria results in an overall task-specific quality Q of 44% for solution n° 5 and 55% for solution n° 6.

5.5 Verification of results

According to Blessing and Chakrabarti (2009, p. 125), four different types of validity listed in Table 6 have to be considered to verify the results of descriptive studies.

Constructing validity of causes and effects stands for the adequacy of the measures used in the study. In this work, all measures used for analogy categories and quality were based on existing research (e.g. analogy categories), so that the results are comparable to other research. To ensure the validity of causes and effects, a possible bias by the researcher has to be excluded. A common approach to reduce the researcher’s bias is to analyse the results with several experts and to calculate a value for inter- encoder reliability. A disadvantage of this approach is that the different experts can still be biased towards the results. Therefore, in this work, two measures were taken: First, the solution ideas were split up according to their working principles (see examples in Table 5). The analogy categories and the quality of the working principles were then analysed by comparing all generated solution ideas. In this manner, the researcher analysed the solution ideas’ quality without regard to the analogy categories and the analogy categories without regard to the pairs. Second, a second reviewer evaluated analogy categories and quality of the solution ideas. The reviewer was a master student with experience in bio-inspired design who was not involved in the presented research. He was provided with the tasks, the biological information, and definitions of the analogy criteria and of the quality criteria (see Tables 2, 4, Fig. 3 and additional material). The inter-encoder reliability was calculated according to Blessing and Chakrabarti (2009, pp. 120–121) and is displayed in Sect. 6.

To ensure covariation between dependent and independent variables, the **statistical conclusion validity** is tested. Different statistical tests are used in this work:

For research question 1, a parametric statistical test is used to compare the influence of the solution ideas’ analogy categories. As the number of solution ideas is 196 (higher than 30), a normal distribution can be assumed, a prerequisite for a parametric test. In this work, ANOVA and Tukey’s range tests are used to compare between the three groups of solution ideas (for details, see Sachs 2004; Rumsey 2013).

For research question 2, the non-parametric Wilcoxon rank-sum test (also called Mann–Whitney U test or Mann–Whitney–Wilcoxon test) is used to compare the single disciplinary and engineer–biologist/support pairs. A non-parametric test is used, because the number of pairs is lower than 30, so that no normal distribution of the data can be assumed. The Wilcoxon rank-sum test has been used by a number of design researchers (e.g., Kurtoglu et al. 2009; Lenau et al. 2015). The Wilcoxon rank-sum test is based on three conditions (Rumsey 2013, p. 306): The two data sets that are compared must have the same distribution and variance and have to be independent. The histograms of the data sets of this study show similar distributions and variances—exemplary histograms are shown in the additional material (1.7).

The condition of independent (unpaired) samples is strictly speaking not fulfilled, because each participant took part in both a single disciplinary and an engineer–biologist pair/support pair. As the impact of the pair composition is the focus of this work, the influence of the individual participants is neglected. Still, order effects due to fatigue or learning are paid heed (see internal validity below).

Table 6 Measures for the verification of results based on Blessing and Chakrabarti’s (2009, p. 125) types of validity

Type of validity	Measures	Section
Construct validity of causes and effects	Division and categorisation of solution ideas on the working principle level, inter-encoder reliability test	5.2, 6.3
Statistical conclusion validity	Application of ANOVA, Tukey’s range test, and Wilcoxon rank-sum test	6.1, 6.2
Internal validity	Test for order effects—using three individual tasks in a pre-test, post-test 1, and post-test 2 (see Sect. 4.4)	6.3
External validity	Influence of three different design tasks	6.3

The **internal validity** ensures that a cause-and-effect relationship exists between the co-varying independent and dependent variables. For this work, the assignment of participants to pairs and order effects were taken into consideration in the study design.

The assignment of participants to pairs was due to their date of participation and the drawing of a lot. As the participants had different research areas, every pair united different areas of expertise.

Order effects are possible both involving the participants and the researcher. To test for order effects of the participants, the individual tests were conducted before, between, and after the ideation in pairs. The results are shown in Sect. 6.3. Here, a modified version of the Wilcoxon rank-sum test is used: the Wilcoxon signed-rank test for paired samples. It tests whether the decreasing/increasing number of aspects listed by the participants in the individual tasks is significant (Rumsey 2013; Sachs 2004).

To exclude the influence of order effects on the researcher, a preliminary analysis was conducted. The final analysis of the solution ideas was then conducted all at once, independent of the order of the design experiments.

For **external validity**, the sample of participating doctoral candidates has to be representative of engineers and biologists. This cannot be ensured, but participants were chosen with a wide range of expertise. The artificial experimental setting was designed to resemble a real ideation workshop. In addition, three different design tasks were used to cover a range of possible tasks and reduce the influence of a particular task on the results. The impact of the different tasks is examined in Sect. 6.3.

6 Results

This section presents the results of the analysis with respect to the two research questions: to answer research question 1, the influence of the analogy categories on the quality of solution ideas is inspected (Sect. 6.1). To answer research question 2, the influence of the collaboration between engineers and biologists and of the use of the *BioId Support* on the analogy categories is examined (Sect. 6.2). As explained in the previous section, additional measures were taken for the verification of the results (Sect. 6.3).

For the analysis, the solution ideas generated by the 20 pairs are studied: The pairs generated 196 solution ideas on the embodiment level, which included 187 solution ideas on the working principle level.

6.1 Research question 1: influence of analogy categories on quality

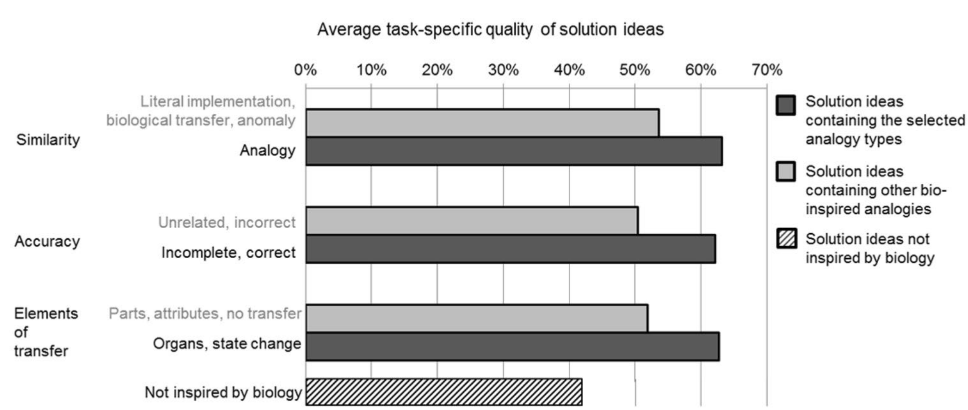
As explained in Sect. 5.2, all solution ideas on embodiment level are analysed with regard to their working principles. On the level of working principles, the analogy categories are identified. As explained in Sect. 5.3, we regard the selected analogy categories, i.e., *incomplete/correct* analogies (*accuracy* according to Mak and Shu 2004b; Vakili et al. 2007), *analogies* (*similarity* according to Mak and Shu 2004a), and *organ/state change transfer* (*elements of transfer* according to Sartori et al. 2010). Their influence on the quality of solution ideas is compared to bio-inspired solution ideas containing other analogy types and to solution ideas not inspired by biology. The results are displayed in Figs. 6 and 7.

Figure 6 shows the comparison of the task-specific qualities: The average task-specific quality Q of the solution ideas containing the selected analogy categories is highest with approximately 60%. The average task-specific quality Q of other bio-inspired solution ideas is approximately 50%. The average task-specific quality Q of solution ideas not inspired by biology is lowest—approximately 40%.

The significance of this observation is tested with an ANOVA (parametric test, more than two samples):

- Null hypothesis: There are no differences between (1) solution ideas containing the selected analogy categories, (2) solution ideas containing other bio-inspired analogies, and (3) solution ideas not inspired by biology.

Fig. 6 Task-specific quality Q of solution ideas



- Alternative hypothesis: At least two of the samples (1–3) differ with regards to task-specific quality Q.

The results of the ANOVA are shown in Table 7. With a probability lower than 5% which is a commonly assumed value for conducting the ANOVA (Rumsey 2013), the two conditions for rejecting the null hypothesis are fulfilled for accuracy, similarity, and elements of transfer (see right column of Table 7).

As the ANOVA only shows that there are differences between one of the samples, we have to test which samples differ. We use Tukey's range test, to test which samples differ significantly. Table 8 displays the results.

The Tukey's range test compares all samples (1–3) to each other. It calculates a q value which is compared to a

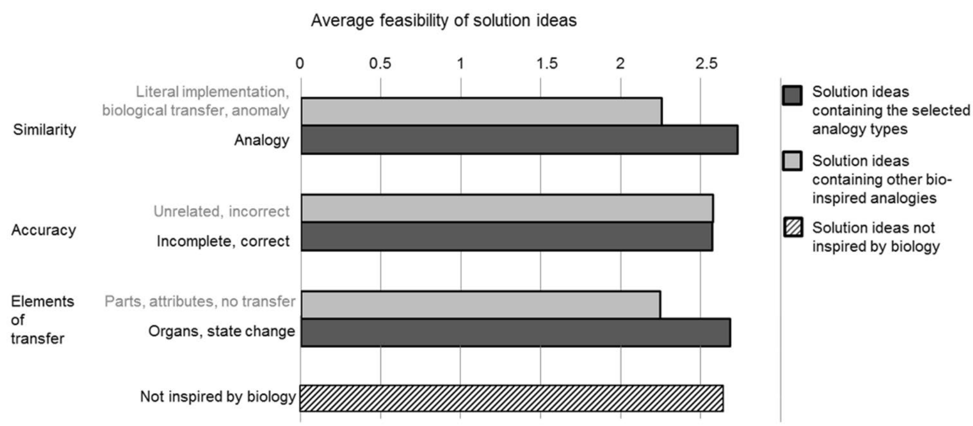


Fig. 7 Average feasibility F of solution ideas

Table 7 Results of the ANOVA (probability of error α = 5%)

	Accuracy (1) Incomplete or correct analogies (2) Unrelated or incorrect analogies (3) Not inspired by biology	Similarity (1) Analogies (2) Literal implementation, biological transfer, anomaly (3) Not inspired by biology	Elements of transfer (1) Organ or state change transfer (2) Copy parts, transfer attributes, no transfer (3) Not inspired by biology	Interpretation of the results: The two conditions for rejecting the null hypothesis are fulfilled
F statistics	8.30	8.44	8.27	F statistics > $F_{critical}$ value
$F_{critical}$ value	3.04	3.04	3.04	
p value	0.00035	0.00031	0.00036	p value < α

Degrees of freedom within groups $df = 193$

Table 8 Results of Tukey's range test (probability of error α = 5%)

Q value (comparison between two samples)	Accuracy (1) Incomplete or correct analogies (2) Unrelated or incorrect analogies (3) Not inspired by biology	Similarity (1) Analogies (2) Literal implementation, biological transfer, anomaly (3) Not inspired by biology	Elements of transfer (1) Organ or state change transfer (2) Copy parts, transfer attributes, no transfer (3) Not inspired by biology	Interpretation of the results: Q value = 3,36 (for $df = 120$) $q > Q$?
q value (1) × (3)	5.62	5.71	5.72	Significant difference
q value (2) × (3)	1.5	2.00	2.57	No
q value (2) × (1)	2.60	2.70	2.58	No

tabulated Q value (studentized range distribution). Here, we took the Q value for $df = 120$ (120 degrees of freedom) as a conservative estimation, as there were no tabulated values for the ANOVA's degrees of freedom ($df = 193$) (Rumsey 2013; Sachs 2004).

The comparison shows that for accuracy, similarity, and elements of transfer, the solution ideas containing the selected analogy categories significantly differ from the solution ideas which are not bio-inspired: The task-specific quality of the solution ideas containing the selected analogy categories is higher [confirmation of hypothesis (1) for research question 1].

In addition to task-specific quality, the feasibility of the solution ideas is taken into consideration. The results are depicted in Fig. 7: Feasibility is evaluated on a scale from 0 to 3 (see Table 4). As the figure shows, the average feasibility of solution ideas containing *analogies* (similarity) and *organ/state change* transfer (elements of transfer) is higher than the average feasibility of solution ideas not inspired by biology and other bio-inspired solution ideas. Solution ideas containing *incomplete/correct* (accuracy) analogies have a similar feasibility as solution ideas not inspired by biology and other bio-inspired solution ideas.

This result is surprising, as bio-inspired solution ideas are based on between-domain analogies (see Christensen and Schunn 2007). They are, therefore, expected to be more unusual than solution ideas not inspired by biology. This was expected to result in less feasible solution ideas, e.g., because the solution contains unusual components and materials (see feasibility criteria in Table 4). However, the results of this study show no decrease in average feasibility, especially not for the selected analogy categories.

6.2 Research question 2: influence of supported collaboration between engineers and biologists on analogy categories

As a next step, the influence of the collaboration between engineers and biologists and the *BioId Support* on the selected analogy categories is analysed. Single disciplinary pairs of biologists or engineers are compared to engineer–biologist pairs. Half of the engineer–biologist pairs worked with the *BioId Support*. The proportion of the selected analogy categories was calculated for all generated solution ideas (documented and undocumented solution ideas) and separately for the documented solution ideas. Figure 8 shows the results:

Considering all generated solution ideas, the figure shows that biologist pairs and engineer–biologist pairs (without support) transfer a slightly higher proportion of *correct* and *incomplete* analogies than engineer pairs on average. Support pairs transfer the highest average proportion of *correct* and *incomplete* analogies. With regards to *analogies* (similarity), the result is similar. Regarding elements of transfer, the highest average proportion of *organ* and *state change* transfer was achieved by the support pairs, followed by the engineer–biologist pairs without support, the engineers, and, finally, the biologists.

The engineer and biologist pairs' average proportion of selected analogy categories is similar between the documented and all solution ideas. In comparison to the single disciplinary pairs, the engineer–biologist pairs without support documented a higher proportion of all selected analogy categories on average. The highest average proportion of all selected analogy categories was documented by the support pairs.

To summarise, biologist and engineer pairs transfer and document a similar proportion of analogies of the selected analogy categories on average. Engineer–biologist pairs without support transfer a similar proportion, but document

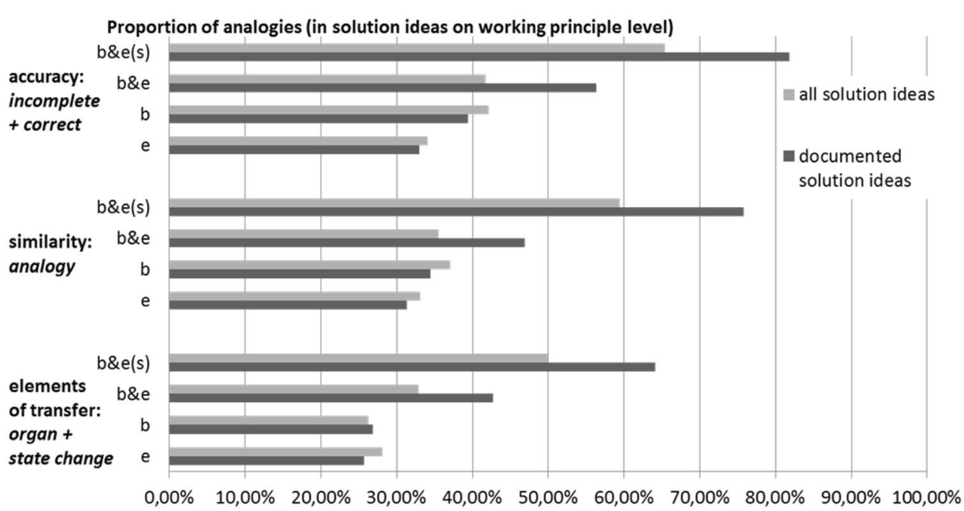


Fig. 8 Average proportion of the selected analogy categories for different pairs [*e* engineer pairs, *b* biologist pairs, *b&e* engineer–biologist pairs, *b&e (s)* support pairs]

a higher proportion on average. Support pairs transfer and document the highest proportion of the selected analogy categories on average.

In a next step, the significance of these numbers is scrutinised both for the collaboration without support and with support. The null and alternative hypotheses are:

- Null hypotheses: There is no difference between single disciplinary and (1) engineer–biologist pairs/(2) support pairs
- Alternative hypotheses: (1) Engineer–biologist pairs/(2) support pairs transfer/document a higher proportion of *correct* and *incomplete* analogies (accuracy), *analogies* (similarity), and *organ* and *state change* transfer (elements of transfer) than single disciplinary pairs

The null hypotheses are tested using the Wilcoxon rank-sum test presented in Sect. 3.2. Table 9 shows the probability of error α for the rejection of the null hypothesis.

To start with, engineer–biologist pairs without support are compared to single disciplinary pairs: Comparing the proportion of the selected analogy categories in all generated solution ideas, the probability of error is higher than 10%. Despite the different average values, the differences between single disciplinary and engineer–biologist pairs working without support are not distinct enough to be significant. The result of the Wilcoxon rank-sum test is different for the documented solution ideas: With regards to *accuracy*, the probabilities of error are lower than 10%. It can be deduced that with a probability higher than 90%, the engineer–biologist pairs documented a higher proportion of *correct* or *incomplete* analogies.

In a next step, support pairs are compared to single disciplinary pairs: With regards to *accuracy*, the probabilities of error are lower than 10% for all and lower than 0.2% for documented solution ideas. It can be deduced that support pairs transfer and document significantly more *correct* and *incomplete* analogies than single disciplinary pairs. As to *similarity*, the probability of error is above 10% for all and below 1% for the documented solution ideas. Regarding *elements of transfer*, the probability of error is above 10% for all but below 10% for the documented ideas. To summarise, a statistical significance with a *probability* of error lower than 10% can be shown for the documented solution ideas.

In conclusion, the collaboration between engineers and biologists has a positive influence on the documentation of solution ideas which include analogies of the type *incomplete* or *correct* (accuracy) and *organ* or *state change* transfer (elements of transfer).

Apparently, the observed tendencies for engineer–biologist pairs are strengthened by the *BioId Support*, which has a positive influence on the transfer and documentation of the selected analogy categories: The support pairs transferred a significantly higher proportion of the analogy categories *incomplete* or *correct* (accuracy). They documented a significantly higher proportion of solution ideas based on all selected analogy categories than single disciplinary pairs.

6.3 Verification of results

This subsection explains the measures taken to ensure internal validity (order effects) and external validity (influence of tasks).

6.3.1 Construct validity of causes and effects: inter-encoder reliability test

The evaluation of analogy categories and the quality of solution ideas on working principle level were conducted twice. The result of the researchers' evaluation was compared to an evaluation by a master student (see Sect. 5.5). The calculated inter-encoder reliability for analogy categories was 76% (accuracy), 84% (similarity), and 71% (elements of transfer). For feasibility, it was 80%, and for task-specific quality, it was 77%. These results are above the acceptable minimum of 70% (Blessing and Chakrabarti 2009, p. 120–121).

6.3.2 Order effects

The individual tasks described in Sect. 3.1 were analysed to test for possible order effects: Did the participants increase their capabilities in bio-inspired design due to the ideation in single disciplinary and engineer–biologist/support pairs?

Table 9 Results of the Wilcoxon rank-sum test for comparing single disciplinary and engineer–biologist/support pairs

Solution ideas	Accuracy Percentage of incomplete and correct analogies		Similarity Percentage of analogies		Elements of transfer Percentage of organ and state change transfer	
	All	Doc.	All	Doc.	All	Doc.
Engineer–biologist pairs (no support)	$\alpha > 10\%$	$\alpha \leq 10\%$	$\alpha > 10\%$	$\alpha > 10\%$	$\alpha > 10\%$	$\alpha > 10\%$
Support pairs	$\alpha \leq 10\%$	$\alpha \leq 0.2\%$	$\alpha > 10\%$	$\alpha \leq 1\%$	$\alpha > 10\%$	$\alpha \leq 10\%$

α: Probability of error (two-sided test)

Or did their performance decrease as they became tired after the 40 min ideation experiments?

The participants named a total number of 504 biological and technical aspects and corresponding technical applications or biological models (a complete list is shown in the additional material 1.8). Post-test 1 and post-test 2 shows examples of similar aspects of biological and technical systems named by different participants. Apparently, different participants had similar ideas for aspects in pre-test, post-test 1, and post-test 2.

Qualitatively, the level of detail is seen as an indicator for the quality of the aspects: If the participants name only components of biological and technical systems, the level of detail is considered low. If the properties or functions of both biological and technical system are detailed as for the examples in Table 10, the level of detail is considered high. Both aspects with low and high levels of detail occur several times in pre-test, post-test 1, and post-test 2. For example, for the technical system, *aeroplane* "wings" or "wing shape" are named four times without detailing which aspect of the wing can be improved by bio-inspired design (low level of detail). Several participants go more into detail and name "surface texture" or "shape of the wings" whose aerodynamics can be improved by bio-inspired design (high level of detail).

Quantitatively, the number of aspects of biological and technical systems was counted and added up for each participant and each individual test. Details are shown in the additional material (1.8). The results show an average difference after the ideation in single disciplinary pairs of − 6%. After the ideation in engineer–biologist pairs, the average difference is − 11% in comparison to the pre-test.

To test for the significance of this observation, the Wilcoxon signed-rank sum test is used with the following null and alternative hypotheses:

Null hypothesis: There is no increase or decrease in the number of listed biological and technical aspects after the ideation in single disciplinary pairs (post-test 1)/engineer–biologist pairs (post-test 2).

Alternative hypothesis: Participants list fewer aspects of biological and technical systems after the ideation in single disciplinary pairs (post-test 1)/engineer–biologist pairs (post-test 2).

The result of the Wilcoxon signed-rank test is displayed in Table 11. The table shows that the probability of error is above 10% for the alternative hypothesis in the comparison of both post-tests to the pre-test. It can be assumed that the observed decrease in the average number of listed biological and technical aspects is not significant.

To conclude, both the qualitative analysis (level of detail of the aspects) and the quantitative analysis (number of aspects) show no decrease or increase of the participants' performance in bio-inspired design throughout the experiments.

Table 10 Examples of similar aspects of biological/technical systems from individual tasks (in brackets: number of aspect in additional material 1.8)

Biological/technical system	Examples of similar aspects named by different participants		
	Pre-test	Post-test 1	Post-test 2
Elephant	Cooling of the blood through large ear surface (2)	Ears for cooling → large area for cooling blood in the ear (293)	Big ears with large surface to emit heat (223)
Dolphin	Body shape: streamlined shape (136)	Streamlined shape (42)	Streamlined shape (314)
Robot	Carrying heavy weights in comparison to own weight, e.g., by means of having several legs (169)	Walking on 8–4–2 legs (70)	Ability to carry weights and mobility (328)
Aeroplane	Surface texture regarding friction (267)	Outer layer, aerodynamics (388)	Surface/wings: low friction (129)

Table 11 Results of the Wilcoxon signed-rank sum test with n: number of participants with a decrease or increase in the number of listed aspects (participants who wrote down an equal number of aspects are excluded, and therefore, $n < 20$)

	After ideation in single disciplinary pairs (post-test 1) $n = 15$	After ideation in engineer–biologist/support pairs (post-test 2) $n = 19$
Rank sum (participants listing fewer aspects than in pre-test)	$R_1 = 78$	$R_1 = 60.5$
Rank sum (participants listing more aspects than in pre-test)	$R_2 = 42$	$R_2 = 129.5$
Probability of error (one-sided/two-sided test)	$\alpha > 10\%$	$\alpha > 10\%$

6.3.3 Influence of the tasks

To ensure that the results are independent of the three design tasks, the quality values are studied separately for each task. The resulting diagrams are shown in the additional material (1.9).

In terms of task-specific quality, the absolute values differ: for example, when comparing the sun protection task to the aquaplaning task, the average task-specific quality values in all solution idea categories are higher. A possible explanation is that the aquaplaning task was more difficult to solve for the pairs.

Still, the overall tendencies are the same for all tasks and in accordance with the results from the descriptive study. Only for the task *"Attachment of Water Pump"*, the solution ideas containing *analogies* (similarity) have a slightly lower average task-specific quality than other bio-inspired solution ideas. Apart from this exception, the solution ideas containing the selected analogy categories have the highest average task-specific quality. Other bio-inspired solution ideas have the second-highest task-specific quality, with the ones not inspired by biology lowest.

Regarding the average feasibility of solution ideas, the results for the single tasks show more variability than the results of the descriptive study. For example, for the task *"Attachment of Water Pump"*, the average feasibility of solution ideas not inspired by biology is highest (2.73). However, the difference to the average feasibility of solutions containing *organ* or *state change* transfer (2.71) is small.

The conclusion from these results is that the influence of the tasks is negligible and the results of the study do not depend on the tasks.

7 Discussion of the results in context of related research

The results of this work can be compared to related research. Table 12 shows research published within the past 10 years on (1) the influence of analogies and (2) the influence of teams and support in bio-inspired design.

With regards to analogies, a number of researchers have examined their influence on several aspects of solution ideas: Cheong et al. (2010) found that *correct* analogies (in terms of accuracy) correlated with novel, useful, and cohesive solution ideas. Usefulness corresponds to a high quality of solution ideas. This research only showed statistical significance for a group of designers using a support for bio-inspired design. Other researchers concentrated on the effect of analogies on novelty (Keshwani and Chakrabarti 2017), on the number or variety of solution ideas (Lopez et al. 2011; Srinivasan et al. 2013; Wilson et al. 2010), or on a combination of both (Gonçalves 2016, pp. 121–146). These findings are, therefore, an additional indicator for the positive influence of analogies on the innovative potential of solution ideas. An additional aspect is addressed by Lopez et al. (2011)—the designers participating in their study had to rate the usefulness of their analogies. With increasing

Table 12 Related research [designers: n° (number): 1 = single designers, t = design teams; prof (profession): eng = engineering, des = industrial design/architecture; level: s = bachelor or master student, m = master's degree, and dr = PhD]

References	Results	Designers		
		N°	Prof	Level
1. *Influence of analogies*				
Cheong et al. (2010)	*Correct* analogies positively correlate with novel, useful and cohesive solution ideas (only designers using a support)	1	eng	s
Wilson et al. (2010)	Designers generated different solution ideas after being exposed to technical or biological examples	1	eng.	s
Lopez et al. (2011)	The number of ideas increased with the semantic distance of technical examples; designers rated the usefulness of analogies from semantically more distant examples lower than those from semantically closer examples	1	eng	s
Srinivasan et al. (2013)	The number of analogies correlated highly with the variety and number of solution ideas	1	eng?	s, m?
Gonçalves (2016), pp. 121–146	Distant analogies increased creativity (fluency, flexibility, originality) of solution ideas	1	des	s
Keshwani and Chakrabarti (2017)	Biological analogies (on low abstraction levels) increased the novelty of solution ideas	1/*t*	eng	s, m
2. *Influence of teams and support in bio-inspired design*				
Cheong et al. (2012)	Design teams Fixate on analogies on low levels of abstraction Fixate on mapping several features of one biological system to one technical solution	*t*	eng	s
Keshwani et al. (2017)	Teams using biocards for ideation generated concepts with higher novelty than teams using brainstorming	*t*	eng des	s, m, dr

distance between the analogue and the technical problem, the designers' ratings decreased. However, their negative ratings are not in accordance with the researchers' criteria for assessing the variety of solution ideas—Lopez et al. (2011) found a positive influence of the distant analogies. This mismatch between designer feedback and researcher evaluation was also observed in the questionnaires used in our study: For example, the pairs of mechanical engineers rated their solution ideas disproportionally positive (see Hashemi Farzaneh 2016).

As to the influence of teams in bio-inspired design, Cheong et al. (2012) observed fixation on several levels: First, design teams fixated on analogies on low levels of abstraction and failed to explore more abstract analogies. Second, they tried to map several features of one analogy to a technical solution instead of developing multiple technical solutions. These findings underline the importance of supporting teams in bio-inspired design to identify and transfer several analogies from a biological system.

A positive influence of visual and textual representations on team ideation was observed by Keshwani et al. (2017): They found that teams using *biocards* (used in this work to develop the *BioId Support*) for ideation generated concepts with higher novelty than teams conducting brainstorming.

To conclude, most existing research supports the findings of this work. As Table 12 shows, the participants are engineers, industrial designers, or architects, often at student level. Neither biologists nor collaborating engineers and biologists were studied. Moreover, most of the studies which analysed the influence of analogies were conducted on single engineers. None of the studies compared different pairs, teams, or participants with different disciplinary background. This work, therefore, adds a new aspect by focussing on collaboration in pairs and by comparing pairs of biologists and engineers to engineer–biologist pairs.

8 Limitations of this work

This work reports an experimental study with pairs of graduated engineers and biologists, who were doctoral candidates at the author's university. In general, internal validity is an advantage of experimental research, because a number of factors relevant during the study can be controlled for (for example, testing for order effects). However, experimental research has disadvantages as to the external validity or generalisability of the results: It cannot be guaranteed that the observations in the artificial setting of an experiment with a sample of participants are transferable to reality (Blessing and Chakrabarti 2009, p. 85). In this work, the generalisability was increased using a realistic task and timeframe. Since the participants were graduated biologists or mechanical engineers conducting doctoral research at different laboratories, it was assumed that they had expert knowledge in different fields of biology or mechanical engineering. As a limitation, the sample of participants did not represent the whole range of biological or mechanical engineering areas. Moreover, as doctoral candidates, the participants had no working experience in industrial companies or as senior researchers.

In addition, personal characteristics have an influence: For example, the performance of individual participants in a creativity test (remote associate test) has been used to predict the quantity of ideas generated in brainstorming groups (Forbach and Evans 1981). However, the quantity of ideas is just one variable and for ideation in engineering design several other variables play a role (quality, variety, etc.). In addition, the tasks in engineering design are more complex than the task used in the cited psychological study. As the relevance of these factors for ideation in bio-inspired design or engineering design in general is unclear, no tests for personal characteristics were used for this work.

9 Conclusion and outlook

Bio-inspired design aims to transfer analogies from biology to develop novel technical solutions with a high potential for innovation. Innovative technical solutions are based on high-quality solution ideas. Therefore, the first aim of this work was to understand the impact of different types of bio-inspired analogies on the quality of solution ideas. The first research question of this work was:

1. How do the analogy categories accuracy, similarity, and elements of transfer influence the quality of solution ideas?

The analysis of the study showed a positive influence of the selected analogy categories *correct/incomplete* (accuracy), *analogy* (similarity), and *organ/state change* transfer (elements of transfer) on the quality of solution ideas. This result was statistically significant and demonstrated that supporting the transfer of the selected analogy categories can have a positive effect. A logical inference is that the definitions of these analogy categories can be useful to train engineers/biologists for bio-inspired analogical transfer. This finding supports and extends the findings of Cheong et al. (2010) who analysed the influence of the analogy categories *correct/incomplete* (accuracy) (see Table 12).

A promising approach to overcome the knowledge gap between biology and mechanical engineering in bio-inspired design is collaboration between engineers and biologists. Therefore, the second research question focused on the influence of biologist–engineer collaboration and their use of a support (the *BioId Support*) on the different analogy categories:

2. How does supported collaboration between engineers and biologists influence the analogy category?

On average, the support pairs (collaboration of an engineer and a biologist using the *BioId Support*) transferred a higher proportion of the selected analogy categories than single disciplinary pairs. For the solution ideas that the participants documented, the positive influence was statistically significant. In comparison, the engineer–biologist pairs working without support documented a higher average proportion of the selected analogy categories as well, but the results were not statistically significant for all analogy categories. This result shows that collaboration between engineers and biologists positively influences ideation, but needs to be supported, for example by a tool such as the *BioId Support*. Its templates strengthen the positive influence of the engineer–biologist collaboration on the transfer of the selected analogy categories, the documentation of the resulting solution ideas, and thereby on their quality.

The main result involving both research questions is illustrated in Fig. 9.

Despite its positive influence on quality, the use of the *BioId Support* had two disadvantages: On average, the number of solution ideas was lower in comparison to the other pairs. Moreover, the participants provided negative feedback on the usability of the *BioId Support* (Hashemi Farzaneh 2016). Several researchers consider the number of solution ideas an indicator for creativity (e.g., Al-Shorachi et al. 2015; Shah and Vargas-Hernandez 2003). This was addressed by Reinig and Briggs (2008) who examined the relation between the quantity and quality of solution ideas: Their results showed that when participants generated a high quantity of solution ideas, the quality of the later ideas decreased. As the quality of solution ideas indicates the innovative potential of the later product, focusing on the quantity of ideas can be ineffective. To conclude, the *BioId Support* has an overall positive influence, but a friendlier user experience has to be developed to make its use enjoyable.

9.1 Indications for future research

For bio-inspired design in general, the results of this work show a positive influence of the analogy categories proposed by Mak and Shu (2004a, b) and Sartori et al. (2010) on the quality of solution ideas.

For collaboration, this work shows the positive influence of a supported collaboration between engineers and biologists. Independent of the use of the *BioId Support*, “supported” means fostering a structured procedure, the transfer of the intended analogy categories, and the use of graphical representations and sketching.

There are multiple possibilities for future research:

This work focuses on the ideation phase. The outcomes of the ideation phase are solution ideas, which have to be evaluated and further developed. As a next step, the influence of collaboration between engineers and biologists during the evaluation process and further development activities can be studied: What impact does discipline-specific knowledge have on evaluation and further product development activities? How does this knowledge change the outcomes?

Another aspect can be to study the participants individually: The results of this work can be analysed with regards to the performance of the individual participants in a single disciplinary pair and an engineer–biologist pair. This can lead to a detailed understanding of discipline-specific requirements for the use of a collaboration support.

9.2 Indications for industrial practice

As the design experiments were conducted in a realistic setting, the results of this work can be used in the design of ideation workshops in industry: For the composition of a

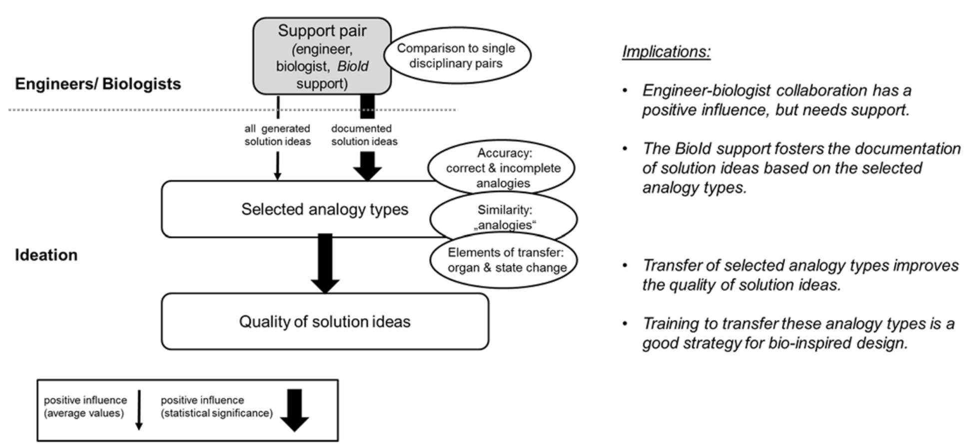


Fig. 9 Overview of the results

pair, group, or team, this work indicates the usefulness of collaboration between mechanical engineers and biologists. Moreover, this works shows the usefulness of templates that foster the adoption of a structured approach and the use of graphical representations and sketching.

The *BioId Support* can be developed into a complete ideation method for collaboration between engineers and biologists. To achieve this aim, workshops with experts from biology, mechanical engineering, and visualisation can be conducted. The main aspect to be improved is the time effort needed to understand and use the *BioId Support*. Moreover, the user satisfaction and fun have to be improved, e.g., by providing the *BioId Support* as software on a drawing tablet—this opens up additional possibilities for (automated) visualisations and an automated workflow. These might raise the participants' interest in the method.

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