User requirements for analogical design support tools: Learning from practitioners of bio-inspired design

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When designers develop biologically-inspired design (BID) solutions, they are engaging in a process of analogical design. Software tools have been developed to support analogical design processes, presenting designers with information to help in the construction of useful analogies. However, the requirements for such tools have not been explicitly informed by accounts of practitioners' experiences. To address this, interviews were conducted with 14 expert practitioners in BID to understand how they find and apply cross-domain analogies. Three main themes emerged from the analysis: (1) the skill sets of individual practitioners; (2) the ways they work as part of an interdisciplinary team; and (3) their orientations to biology. These themes present opportunities and challenges for developing analogical design support tools.
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Analogical thinking involves the transfer of information from one domain (the source) to another domain (the target). This is widely considered to be an important process in creative design and innovation (Chan et al., 2011; Dahl & Moreau, 2002; Enkel & Gassmann, 2010; Herstatt & Kalogerakis, 2005; Kalogerakis, Lüthje, & Herstatt, 2010). Biologically-inspired design – BID (also referred to as biomimetics or biomimicry) is a good example of this as it is a design practice which involves identifying and applying analogies from the biological domain to the technical domain. To assist with BID processes, design researchers have developed computer support tools that store and present information about biological and technical systems, so that possible connections can be identified. However, these analogical design support tools have seemingly been developed based on limited information about real-world user needs. Instead, they are primarily based on theory (from multiple fields), student BID projects (with or without access to information tools) and historical anecdotes (often quite brief accounts).

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To better understand the requirements for analogical design support tools, we here report on an interview study of professional BID projects. We discuss the expectations that BID practitioners have for software tools by addressing three main levels of analysis in relation to BID practices: the skill sets of individuals involved in BID; the ways in which individuals work together as part of interdisciplinary teams; and the ways in which those individuals or teams orient towards biology. We show the ways in which software tools could be employed at all three levels in order to support BID processes, and we illustrate the variety of BID processes that might be relevant. These findings advance our understanding of analogical design and our understanding of the requirements for analogical design support tools. Ultimately, by exploring these requirements we intend to provide a more solid foundation upon which analogical design support tools can be developed and deployed.

1 Literature review

Analogical transfer is useful when there is some similarity between the source and the target domains (or the relations in those domains) and where that similarity permits reasoning across domains (e.g., Gentner, 1989; Vosniadou & Ortony, 1989). Where the source domain is familiar and accessible, drawing analogies can make new subjects easier to understand, facilitating the discovery, development, evaluation and exposition of (natural and social) scientific knowledge (Holyoak & Thagard, 1995, pp. 191, 209). Consequently, analogies are prominently used in many professional practices, including science (Oppenheimer, 1956), medicine (Clarke, 1978), management (Bingham & Kahl, 2013), and education (Dupin & Johsua, 1989). Analogical thinking is also central to much design activity, where it serves in identifying and solving design problems and in explaining design concepts to others (Christensen & Schunn, 2007). Collectively, these aspects of analogical thinking provide the opportunity to generate creative design proposals that lead to innovative products, systems, and services (Chan et al., 2011; Dahl & Moreau, 2002; Hey, Linsey, Agogino, & Wood, 2008; Kalogerakis et al., 2010).

One of the most difficult challenges in constructing analogies is the retrieval of a plausible source, especially where the search space is large and where the relationship to the target is not obvious (Holland, 1986, pp. 288–289, 312). Such challenges have led to suggestions that it is helpful to have a catalogue of possible sources to draw from and some means of identifying those sources that are related to the targets that are being considered (Linsey, Wood, & Markman, 2008). In response to this need, design researchers have developed computer support tools that assist in the construction and application of both cross-domain analogies (e.g., Chakrabarti, Sarkar, Leelavathamma, & Nataraju, 2005; Shu, 2010; Vattam & Goel, 2011; Cheong & Shu, 2012, pp. 373–382; Goel, Vattam, Wiltgen, & Helms, 2012) and within-domain analogies (e.g., Barber et al., 1992; Maher, Balachandran, & Zhang, 1995; Pearce et al., 1992).

Many analogical design tools represent biological systems as the information source so that those tools can support the process of biologically inspired design (for brief reviews see Arlitt, O'Halloran, Novak, Stone, & Tumer, 2012; Fu, Moreno, Yang, & Wood, 2014; Glier, McAdams, & Linsey, 2011; Goel, McAdams, & Stone, 2014; and see Wanieck, Fayemi, Maranzana, Zollfrank, & Jacobs, 2017 for a more detailed overview). Some databases adopt a functional modelling approach to structuring the content, listing possible analogical sources from biology ('DANE' - Goel et al., 2012) as well as artificial systems ('Idea-Inspire' - Chakrabarti et al., 2005). These systems classify the content based on function—structure ontologies and make that content searchable with user-defined queries. Additionally, some tools also invite experts to create the content collaboratively ('AskNature' - Deldin & Schuknecht, 2014). Compiling these databases is labour-intensive, requiring information to be identified and formatted to the system's requirements. Sources such as text books, scientific papers and websites provide more open-ended possibilities for identifying potential analogies, however it is difficult to search through them as the language adopted by biology is often different to that used in engineering (Shu, 2010). There are efforts to translate this knowledge by using natural language processing approach ('BioMAPS' - Cheong & Shu, 2012, pp. 373—382) and translation guides to assist with the search process ('Engineering-to-biology thesaurus' - Nagel, Stone, & McAdams, 2010).

In research settings, these tools often serve two interconnected purposes. First, they are developed to promote and support analogical thinking in design practice (or they represent the types of systems that could do so). Second, use of these tools provides a basis upon which analogical thinking activities can be studied in observational or experimental research. As such, the tools are both the manifestation of knowledge about analogical design and one of the means by which that knowledge is generated. Of course, the ultimate aim of analogical design support tools is to provide stimuli that assist in the construction of analogies and thus facilitate creative design work (Deldin & Schuknecht, 2014). This creative work might be evident in the design solutions that designers arrive at or in the problem reframing activities that occur during the design process (Goel et al., 2012).

A range of analogical design support tools have been evaluated, either individually or comparatively, and with respect to quite objective performance measures and also more subjective user feedback. For example, the tools have been theoretically analysed based on the issues addressed in the literature (Fu et al., 2014), and also assessed with students in educational settings, including measures of usability and usefulness (Arlitt et al., 2012), based on both quantitative (Vandevenne, Pieters, & Duflou, 2016) and qualitative data (Goel et al., 2012). Professional participants have also been involved in tool evaluation, with the general usefulness of the tools being assessed (Chakrabarti et al.,

2005) and the most appropriate design stages for tool use being identified (Fayemi, Wanieck, Zollfrank, Maranzana, & Aoussat, 2017).

Although many analogical design support tools have been developed, studied and evaluated, there is little documentation of the user requirements for such tools. A better articulation of user requirements would offer at least two benefits. First, developing design support tools according to a set of user-centred 'needs' promises to decrease development time (by providing clearer goals and information about trade-offs) and also to increase uptake (by improving effectiveness and ease of use). Second, analogy-driven design activities are most easily studied when the tools used to support those activities fit well with the requirements of their users. The need for better software tools is supported by observations of analogy use in professional design practice, with designers criticizing existing tools for not providing effective mechanisms for identifying and applying knowledge from other domains (Kalogerakis et al., 2010, p. 433). The need to adopt a user-centred approach to analogical design tools is recognized in the research community also, with calls to focus on issues of usability, interface design, visualization, and search (Goel et al., 2014). This is part of a more general ambition to develop tools that assist people's creative work without disturbing the natural flow of their activities (Hewett, 2005).

To identify user requirements for software tools supporting analogical design, Töre Yargın and Crilly (2015) reviewed the relevant literature in design, analogy, creativity and human–computer interaction. They proposed a distinction between the information content that the tools should provide (what sort of information the tool should contain about the analogical sources) and what interaction qualities the tools should exhibit (what the tool should be like to use when identifying and applying those sources):

Information content

- *abstraction* – deriving general principles from specific instances
- *exemplification* – illustrating general principles with specific instances
- *mode of representation* – displaying text, drawings, photographs, etc.
- *open-endedness* – permitting different, interpretations of the information
- *concision* – balancing brevity with completeness
- *multiplicity* – maintaining diversity and variety of content

Interaction qualities

- *accessibility* – allowing easy retrieval of the content
- *interactivity* – providing active control and continuous feedback
- *transparency* – providing clarity in interaction
- *connectivity* – integrating the tool with other systems

- *shareability* – allowing content to be communicated to other stakeholders
- *restoration* – permitting the resumption of previous activities
- *adaptability* – allowing the nature of the interactions to change

The relationships between these requirements were found to be quite complex, with some being mutually supporting, whilst others being in conflict. Töre Yargin and Crilly (2015) concluded that the two key requirements were open-endedness and accessibility, and that tool developers should focus on delivering these first and then look to manage the interactions between the other requirements.

Although Töre Yargin and Crilly's (2015) review is useful in proposing a set of user requirements for analogical design support tools, their study is also limited by the literature on which it is based. That literature is primarily theoretical or experimental in nature, lacking an explicit grounding in the practices of professional designers. As such, we might ask questions about what user requirements would be identified from studying real-world analogical design projects. What does analogical design look like in the wild? How could that process be assisted? What tools or techniques are already in use? What are the limitations of those tools? What are the requirements for future tools? The study reported here seeks to address such questions by surveying BID practitioners' experiences of the process of analogical design and eliciting their opinions on what design support tools should be like. Although there are a variety of possible analogical sources from which designers might draw, we focus on the biological domain (and bio-inspired design tools) for three reasons: (1) because of BID's recent rapid expansion and wide applicability across a range of technologies, problem types, and design disciplines (Lepora, Verschure, & Prescott, 2013); (2) because BID is, by definition, based on cross-domain analogies and thus promotes or permits a wide range of analogical distances (Goel et al., 2014); and (3) because there has been much recent BID tool development work with associated studies of designer interactions with those tools (e.g. see Arlitt et al., 2012; Vandevenne et al., 2016).

2 Methodology

Over a 10 week period, semi-structured interviews were conducted with 14 expert practitioners in BID. This was to understand their experiences and to learn their expectations regarding information tools intended to assist in the identification and application of cross-domain design analogies.

2.1 Sample

To identify professional BID practitioners engaged in real-world projects we searched the AskNature database (Deldin & Schuknecht, 2014) and conducted further internet searches using the keywords 'bio-inspired design', 'biologically inspired design' and 'biomimicry'. For consistency, we limited the search to examples of physical bio-inspired products developed in professional settings, including both academia and industry. To ensure a focus on real-world projects, the products were required to either be commercially available or at a developmental phase that included physical applications or prototypes. Moreover, only products that were already patented or publicised in journals such as *Nature*, *Science* and *Bioinspiration & Biomimetics* were considered. Finally, it was required that there was a clearly identifiable expert associated with the design. The criterion used for defining the most relevant expert for each project was that they should have been responsible for the identification, mapping and transfer of the solutions from the biological domain to the technical domain. From this selective search, 42 products were identified, each with an associated expert. These experts were individually invited to participate in the study, with twenty (48% of 42) responding to the initial invitation and fourteen of those (33% of 42) being available for interview.

Participation in the study was on the basis that the anonymity of people and projects would be preserved. However, those people and projects can still be characterised at a general level (see Table 1), consistent with the objectives of the study. All participants were employed by academic or commercial institutions and had an average of 22 years professional experience (ranging from 3 years to 44 years). The participants were geographically dispersed, spread across four continents. The projects that the participants were associated with represent a diverse range of industrial sectors, which are here described using the Global Industry Classification Standard (GICS).[1]

2.2 Data collection

Because of the participants' geographical distribution, interviews were conducted using internet telephony. This sometimes included a live video stream if the participants preferred (for a discussion of the method, see Deakin & Wakefield, 2014; Hanna, 2012; O'Connor, Madge, Shaw, & Wellens, 2008). Prior to the interview sessions, all participants were sent an information pack, including an informed consent form and an overview of the topics to be addressed in the interview. All participants permitted recordings to be made of the interviews, which averaged 30 min in length. The interviews covered four basic themes: (1) the story behind the example product, (2) how the connection between the inspiration source and the target feature was identified, (3) information search activities related to BID, (4) the prospect of using an information tool for BID.

2.3 Data handling and analysis

The audio recordings were transcribed verbatim and the transcripts were then imported into qualitative analysis software (ATLAS.ti). A combination of deductive and inductive approaches were adopted. The deductive analysis involved coding the participants' contributions with a provisional 'start list' of constructs (see Miles & Huberman, 1994) that had been identified from a

Table 1 Basic educational and professional details for each participant in the study and basic information about the main project they discussed in the interview

ID	*Highest level of Education*	*Professional Experience (years)*	*Professional role on the bio-inspired project discussed*	*Project setting*	*Location*	*Industry that the project served or used (from GICS)*	*Product type*	*Inspired by*
P01	Bachelors	32	Designer	Industrial	North America	Footwear	Sports shoe	Land mammal morphology
P02	Doctorate	34	Biologist	Academic then Industrial[a]	North America	Renewable Energy Equipment & Services	Energy converter	Sea mammal morphology
P03	Bachelors	24	Computer Scientist	Industrial	North America	Office Equipment	Electricity controller	Group behaviour
P04	Masters	3	Designer	Academic	Europe	Toys & Games	Game algorithm	Group behaviour
P05	Masters	25	Architect	Industrial	North America	Construction Supplies & Fittings	Building component	Soft tissue structure
P06	Masters	30	Designer	Industrial	Australasia	Appliances, Tools & Housewares	Cooling device	Plant seed structure
P07	Doctorate	15	Biochemistry expert	Academic then Industrial	Europe	Environmental Services	Liquid processing	Cell filtration mechanism
P08	Masters	5	Engineer	Academic then Industrial	North America	Business Support Services	Security feature	Insect morphology
P09	Doctorate	21	Engineer	Academic	North America	Renewable Energy Equipment & Services	Power source	Energy storage molecule
P10	Doctorate	8	Engineer	Academic	Europe	Robotics[b]	Robotic device	Group behaviour
P11	Doctorate	10	Biologist	Academic	North America	Robotics	Robotic device	Group behaviour
P12	Doctorate	44	Architect	Academic then Industrial	North America	Construction Materials	Building material	Structural material in animals
P13	Doctorate	10	Engineer	Academic then Industrial	North America	Industrial Machinery & Equipment	Robotic device	Morphology of aquatic organisms
P14	Doctorate	41	Engineer	Academic then Industrial	Europe	Auto, Truck & Motorcycle Parts	Ancillary component	Insect behaviour

[a] In all six instances, 'Academic then Industrial' means that the product was first developed in an academic research setting and then adopted by industry.

[b] Robotics is outside the scope of GICS taxonomy. However, it is included in the industrial domain list, since biomimicry is closely related with the robotics field (e.g. according to Lepora et al.'s (2013) analysis on publications regarding biomimicry, robotics is one of the most popular topics in the area) and it is hard to specify a single industrial sector for robots, since they often have more than one area of application. Where applicable, the industry which the robotic device was developed for is indicated as in P13.

review of the relevant literature, as summarised in Section 1. The Inductive analysis involved iteratively reviewing the transcripts to identify new themes in the data and coding the data accordingly (see Thomas, 2006). Two coders independently and iteratively worked through the transcripts, with the resulting analysis combining contributions from both of them.

The main themes emerging from the analysis are reported in Section 3, supported with illustrative quotations from the participants. Wherever possible, we try to allow the 'talking' to be done by the participants, because the voice of professional BID practitioners is largely absent from the tool development literature. Although the analysis was conducted on full verbatim transcripts that reflected pauses, broken sentences and repetitions, the quotations provided here are edited for ease of comprehension. Also, where necessary, certain details of the product, process or market have been described in more general terms to preserve the anonymity of the participants. Where requested, participants were also given the opportunity to edit their quotations for correctness and anonymity. This anonymity is further protected by using gender-neutral pronouns (e.g. 'they' to refer to individuals). Whether for reasons of anonymity or clarity, substantial editorial additions or substitutions are enclosed in square brackets. Otherwise, the language used is entirely that of the participants.

3 Findings

In presenting the research findings we propose three levels of analysis: (1) the skill sets of individual practitioners, with a focus on their personal characteristics and inclinations; (2) the ways in which individuals work together as part of a team, with a focus on interdisciplinary collaboration; and (3) the process of developing BID ideas, with a focus on orientations to biology. We discuss each theme in turn, identifying the most relevant user requirements using the terms proposed by Töre Yargin and Crilly (2015) or defining new ones as necessary. The structure of the (third-level) headings reflects this, with the theme of interest indicated by the main heading and the associated requirements indicated by the sub-heading (e.g. 'Openness to serendipity [theme]: interactivity and adaptability [requirements]').

3.1 The skill sets of individual practitioners

The BID practitioners we interviewed referred to a set of personality traits and characteristics that support creative thinking: *openness to serendipity*; an *interest in multiple fields*; and *personal strengths in navigating these fields and in making cross-domain connections.*

3.1.1 Openness to serendipity: interactivity and adaptability

In the development stories recounted by the practitioners, serendipitous encounters that trigger novel ideas played an important role at the concept stage of the design process. These unexpected instances were described as eureka moments, or epiphanies:

> If you really want to go way, way back, what some people call the eureka moment… Beginning of the 1980s I was in small shop in Boston and had seen a figurine of a [specific sea mammal] and looked at it and thought that the artist had got [its] morphology all wrong… That's not the way it [is] supposed to be [although I later learned it was actually correct]. (P02)

The practitioners sometimes regarded chance encounters as uniquely addressed to themselves, as 'personal happenstances' that linked their own various interests into generating a novel idea. Serendipitous encounters with new information, people, or objects – such as the figurine, in the example above – cannot be programmed or controlled. Letting oneself be inspired is an intimate process that comes from, and is integrated into one's life; it surpasses the domain of work, connecting one's professional activities with pastime activities. Because of this, some participants pointed out that BID tools could not easily replace or mimic the role that chance encounters played in the development of a novel concept.

> I don't use a tool. […] It might work for somebody, it wouldn't work for me… for me it's much more personal […]. You know there is [an existing BID tool] and there are all these techniques and everything… But actually in my case, it's much more integrated into my life. So for example, […], for almost all of my process I can tell you when I got the inspiration, and the inspiration came from my life, not from trying to invent a new material or something. You know, I just wait until the inspirations come out of my life, you know […] like I went to Africa and I learned about how the bones of those early humans were preserved […] So I went home and I tried […] and that led me on to a different kind of [material]. (P12)

In other situations, BID practitioners actively sought chance encounters, and tried to enact them through enhancing their attentiveness:

> I walk through a bookstore or hardware store and I'm visually scanning everything. And if I have something in my mind, things just pop-out, because that's on my mind. (P01)

This cognitive strategy for seeking inspiration was compared to using a search engine:

> If I can touch and feel it, it just all comes together. But if it's just words, or just numbers… you know, that doesn't do anything for me. It's really difficult for me to sort through that, but I know [that for] other people that's their strength. They [would] rather have that than images. But if upfront in

> a search engine …, if you have a way of typing in a kind of questionnaire, and you develop a profile of who you are: are you a visual learner, or what type of learner are you? And when you go to your search, it applies that to your search. So it will give you the same information that it will give to a different learner, but in a different format, so that it's easy to absorb and easier to sort through. That's the big drawback of most search engines. They are not connecting to the individual. They have this sort of brought-in [model], sort of map of applying things to people. (P01)

Thus, there are ways in which software tools could be relevant for BID practitioners in supporting the skill, or the cognitive strategy, of being open to serendipity. For example, existing tools, such as search engines, could be improved to provide tailored information. When search results are adapted in relation to the user's personal traits — such as what type of learner they are — their interaction with the software tool becomes similar, in some ways, to the experience of browsing through a bookshop.

> You know, being able to curate that, or to save your options is really critical, because I do that so it helps me remember what's going on […], but it's time consuming. So your subscribers can contribute and […] tag their own content in a way […]. I think it could be very useful if it's highly personalized in that way. And you know, I'm not a programmer, […] but there must be a way to enable people to curate the experience of [the] database in some way. I think that could be really exciting and keep them coming back, because you'll have their preferences and all of that. So I think, in terms of interaction, I think if you get past the broadcast model, where it's just like 'here's some stuff', and have people contribute a bit or shape it however it suits them, it will be invaluable… (P05)

When users perceive the curation of content they are provided with as unique and tailored to their own personality and interests, they can expect further chance encounters to arise in the way this information is revealed to them, rather than assuming that the tool will provide nothing more than the standard search engine experience. Therefore, if support tools possess the characteristics of interactivity and adaptability then this can enhance opportunities for serendipity by recreating some aspects of personal happenstances.

3.1.2 Interest in multiple fields: abstraction and exemplification, multiplicity and open-endedness

Another skill that the research participants thought was important for facilitating analogical thinking was that of having curiosity and broad interests. In order to work within teams that are developing bio-inspired design, one needs to have, in the first place, an interest in the natural world. This personal interest becomes part of one's skillset when employed in professional settings.

> You've got to have, in my view, the right person in his own discipline with a mind-set which says: 'Wow, that's interesting!' I was trained and have been trained as an engineer with a mathematical background and [...] looking at things logically with man-made machines. I also have an interest in seeing design in the natural world [...] So I think you've got to have that interest in the natural world combined with engineering which then gives the innovative spirit...(P14)

Ultimately, the skill of learning from other fields is what facilitates BID, and contributes to advancing the discipline of engineering:

> I often tell junior engineers, the best kind of science is the one that we learn directly from nature. ... Particularly in engineering, all we're doing is iterating, we're not innovating. If we want to innovate, we have to be always looking outside into nature and looking at areas people haven't looked at... Or looking in a different way. (P08)

There are some ways in which software tools for analogical design can support designers in following a wide range of interests. Regarding the information content of these tools, the participants expressed two main sets of expectations: a good balance between abstraction and exemplification in the way information is presented; and multiplicity and open-endedness, which were described in relation to mixing academic and general knowledge.

A certain level of abstraction is often seen as necessary in order to be able to transfer knowledge from one field to another:

> So what is often missing in the scientific literature in biology is an abstraction of the principles: if it's catchy as a principle, how does this look? [how can the principles be highlighted?] (P10)

However, if the information is too abstract, or too general, it might be difficult to see the ways in which it could be relevant in relation to much more specific design questions:

> I think in a lot of ... research ... the questions you have are so specific, it's very hard to create a general database which has a lot of inspiration, because it will never have that specific answer for you. (P04)

In order to move from generality to specificity in the information content of a database, that information could be presented with a higher degree of exemplification.

The skill of maintaining a wide range of interests and of looking for inspiration in other fields is also supported by the types of knowledge BID practitioners are able to access. Academic and general knowledge were identified as the two main types of knowledge one could employ and mix in order to maintain one's curiosity in other fields. While the ways in which scholarly papers present information could sometimes be inaccessible or incomprehensible – especially for a reader coming from a different discipline – general knowledge would not suffice. Finding the right level of description is one of the main challenges that BID practitioners face, especially at the concept generation stage of the design process.

> I usually spend my first one to 2 h every morning just reading, you know, things like National Geographic, Science, Nature… you know, and a number of other science blogs and artists' blogs. I'm trying to get a scope of what's happening in the world, what people are looking at, what people are being inspired by, and trying to find an inspiration. So definitely having something that consolidates that a little bit would be really useful […] You know, if you're only searching Google Scholar, you're going to miss the *National Geographic* articles, you're going to miss the [press] article or something like that, which can be just as good, just as interesting. You know, when you're starting the early days of research, looking for that inspiration… so, being able to incorporate that and sort of being able to slide that [in] from the outside would be, I think, really important. (P08)

The expectation of multiplicity, which refers to maintaining diversity and variety of content, is expressed here in relation to bringing academic and general knowledge together for cross-fertilization. This mix of knowledge will also support open-endedness, permitting different interpretations of the information in relation to one's own disciplinary background and research questions.

> I mean the way I work… I'm looking at a lot of things, just trying to find some inspiration. So it's really the breadth of information, and you pick up [a] little here and there; it's an overview of things. So for me, having an overview of a lot of things is really good, and then when you find something – so saying that you get more cooling effect from a gust of wind [than] from a constant breeze… So once I've found that information, then I will be looking at …, you know, the [research] papers. (P06)

By providing a mix of academic and general knowledge, analogical design support tools could help BID experts save time in the process of browsing through different information sources, while also potentially supporting a more systematic approach to browsing. Therefore, when the information content of software tools exhibits multiplicity, open-endedness, and a mix of abstraction and exemplification, these tools could be relevant for BID practitioners in maintaining a wide range of interests.

3.1.3 Making connections between domains: cross-disciplinary education

Beyond maintaining interests across a range of fields, BID practitioners need to be able to make connections between domains in order to propose novel applications of cross-disciplinary knowledge. One of the main challenges the research participants identified in this respect is that of navigating through a large amount of information while being able to see connections across disciplines.

> I think the biggest challenge that we have with the […] technology is that we spend so [much] time in different areas. So, what we actually do is that we start with molecular biology, we end up in plumbing. And there is a lot of scientific and technical areas in between molecular biology and plumbing [laughs]. So, I think, we have been in everything, you know, molecular biology, biochemistry, biophysics, membrane engineering to finally more or less to low-tech plumbing… But it is something that is required, and I think it's also something really required for [much] biomimetic technology development, that you have to use a lot of different scientific areas in order to reach your goal. (P07)

The skill of making connections across disciplines can be regarded as a personal strength that belongs to individual designers and that is part of what makes each practitioner and each project unique.

> There are sources out there like this […] for finding out materials for finding solutions. And there is a huge database these people put together and they charge a fee to go online and find things. The part where you kind of get lost is how you apply what's being presented. And I think that's where my strength has been: in seeing things, and then finding [how] to apply them in unique ways. I don't know, maybe there is an art to it, but for me it's just like I become inspired and I see something and then it's almost like I've got a visual image in my head of what I can do with it… That's hard for some people, but that's just how I think. (P01)

Some participants stressed that software tools could not replace individuals' ability to make connections between domains:

> […] What I would call the 'buzz of inspiration' […] you cannot actually programme in a person. […] What really causes 'the buzz' is when somebody […] who has an interest in their own discipline, (which for me is the engineering discipline - I also have an interest in design in nature) sees the implications in what is being studied in nature. So that interest caused me to look at a certain insect behaviour, and to ask 'how does this work in an engineering context?' Now you cannot put a formula for

> that buzz, when somebody gets interested in something, it motivates him to look further. Scientific inspiration cannot be totally programmed. You can provide tools for somebody […], but those won't actually provide the actual inspiration. (P14)

While the 'buzz of inspiration' might not be something that can be programmed into an individual, some practitioners stressed the importance of training and education across fields for supporting the development of the skill of navigating through disciplines and making connections across them.

> … it also needs to be together, like actually working together with humans that are from biology, and some that are trying engineering. A lot of things happen through that. So, [these] departments should be close [to each other], seminars should be organized, programs should be joined between departments. Things like that would be helpful. (P10)

> I think my recommendation would be to get biomimetics taught as a module in engineering degrees. But my main concern is that biomimetics ought to be taught in the biology classes. In other words […] to encourage bio-inspiration, we need to get cross-fertilisation of ideas. Therefore, we need to get more interaction between biologists and engineers. (P14)

Therefore, it could be argued that there is an opportunity for educational software tools – when employed as part of wider cross-disciplinary educational programs – to support BID practitioners in developing skills for making connections between domains. BID tool developers might also consider the multiple users that they are potentially designing for, including not just designers, but also biologists and other members of a cross-disciplinary development team.

3.2 Interdisciplinary collaboration

When individuals work together within teams in order to develop bio-inspired products and technologies, they often have to collaborate with peers coming from other disciplines. In describing their collaborative work practices, the practitioners emphasized the challenge of *cross-disciplinary translation*, and the importance of *visual representations* for communication within teams.

3.2.1 Cross-disciplinary translation: multiplicity and transparency

Specialization in a particular field implies learning the language of the field, which then mediates the ways in which one regards the physical world, and approaches research questions. In interdisciplinary work settings, commitment to only one scientific language can become a form of bias that impedes dialogue and limits the level of innovation that can be achieved. The practitioners talked at length about the importance of understanding the language — *and the worldviews* — of their colleagues and teammates coming from other disciplines. This mutual understanding can be achieved in time, by working together very closely.

> I think the biggest challenge is that, you know, molecular biologists don't talk the same language as the quantum physicists or plumbers even […]. These people have to work so closely that they start talking the same language, […] The same scientific language […] It's one of the biggest challenges, but I also think that it's one of the biggest opportunities that you have, if you can get different scientific areas to understand the other area. There might be a lot of solutions that are already out there. It's just a matter of the specialists in each field being able to understand the other specialists. (P07)

Failure to understand other scientific languages could lead to unwanted surprises at the end of a project, if team members discover that they have been talking about different things all along:

> I mean one of the biggest challenges, I think, when as a biologist [you work with…] mathematicians, engineers etc. is the problem of language. The technical language in different disciplines is very different. Like what we call something is potentially a different thing for the engineers. You know, what they call control theory […] we call it cognition for instance […] It has always been the biggest challenge trying to figure out what is the common language between the disciplines that we can agree on, so we can then move forward in the project without having any bad surprises in the end, because we're not talking about the same thing […] You know, sometimes I would really like to [have a means of] translation [laughs]: you know 'biologist-to-engineer', 'engineer-to-biologist'. (P11)

Any form of cross-disciplinary translation would be beneficial for BID work. The research participants suggested that software tools could incorporate a translation feature, by displaying multiple keywords corresponding to a range of disciplines, for each phenomenon or example discussed. This can be regarded as another reification of the expectation of multiplicity in information content.

> So as I go along I think I learned the literature in biology more… now I would use the keywords that are in the biological literature. […] 'Catapult jump' is something that is used in the biological literature, but not used in robotics; I've never heard these words in robotics. So I would now use more biological [words]. So this could be maybe something to ask when [populating] the database, […] to have the words or keywords, the language of the different disciplines for the same thing. (P10)

Another way to incorporate multiple scientific languages as part of a single software tool would be to allow specialists from each field to add information into the database. 'Open' software provides a means to ensure that the approaches and vocabularies of each discipline are represented, rather than having all information filtered through the lense of any single discipline:

> Thinking again about the open innovation mind-set in how to set up this tool could be very interesting in order to get [...] as many different angles as possible [...] Yeah, just at least making an entry for all the parties to actually put in an input into the database, so it doesn't have to go through, you know, one secretary, one group of people that you actually try to meet often; so open software where everybody can put in information. (P07)

Current software tools are curated by small groups of people and were thus criticised (as the above quote suggests) for presenting limited examples that always have clear evidence of biomimetic possibilities.

> [The available tools,] they're somewhat limited, in that they're going to look at some specific examples, something that's already gone through some maturation. So unless it's already identified as biomimetic, and not everything is always identified as biomimetic, [you won't find it]. Sometimes you just have analogies that they don't realize that there is a potential biomimetic connection. (P02)

Even though an open software system can enable users to overcome the limitation mentioned above, it may also raise questions about credibility. To overcome this, transparency is sought not only in the form of input to the software, but also in relation to the recommendation and reputation systems that might be invoked.

> [There are] two main problems. [First] is getting access to the breadth of information, which is really hard. Sort of, like a reputation system: something that you can, you know, when you get some information that you can trust. Because, especially when you're not from a particular field, it's very hard to figure out what you should read, what you should avoid. (P11)

Therefore, when displaying multiplicity and transparency in the way the information is presented, software tools could support cross-disciplinary translation within BID teams.

3.2.2 Visual cross-disciplinary communication: mode of representation

The BID practitioners emphasized that the visual domain was an important element in their work practices, where being able to visualise the ways in which bio-inspired features would work in a new product, and how the finished product will look and function, were often the first steps in the development of new products and technologies. Some practitioners considered that working together with people from disciplines that privilege visual information, such as the arts, would be beneficial to biomimetic innovation projects.

> You know, coming from the outside, artistic, architecture background […] with the visual eye, I would say… I thought about what happens to the material inside, what happens to the material over time, and so that's how I got to thinking about the kinds of things that I do. I think it's a very important thing to have people come from different fields, especially artists – because artists can visualise. […] I know how it's going to work even before I do it, you know, in a way; because I visualise. (P12)

One BID practitioner recalled that a set of close-up pictures were at the core of the process of understanding a particular feature of an organism, and produced a 'lightbulb moment' (also see Section 3.1.1) during an interdisciplinary meeting.

> So when I visited […] and looked at his laboratory photographs [of the biological system], he could show me the electron micrographs which were very carefully done. He could take a very tiny chamber and he could show me the inlet tube and the exhaust tube of the system. When he showed me the exhaust tube, he had not himself fully understood how that worked. Then I saw that there were flaps of soft cuticle which were resting on hard cuticle. I then realised that it was a pressure release valve […]. That was what I call a light-bulb moment. We understood, between us, what was going on with the biological system (P14)

There are several forms of visual representations that software tools could employ in order to support cross-disciplinary communication within BID teams. First, computer simulations that display a different vantage point, such as from the inside of the organism, could contribute to users' understanding of how the organism works at a molecular level.

> I think tools which help you visualise how nature works are very important in making these connections. Also for scientists, it's very powerful if you can visualise something – even though it might not be direct visualisation, it could only be a computer simulation that is visualised. It is when you sort of accept how nature works on a molecular level. (P07)

Second, the general visual display features of search engines were mentioned as examples of software tools that can render a wide range of information accessible in one glance. BID practitioners often used visual searches when looking for inspiration resources:

> Often when I'm looking for some inspiration on something, I'll search for terms and I'll just look at Google images. I'll see what kinds of figures are out there, and that figure might lead to a paper that's interesting. I'm a very visual person and I like this; I like to see the images, you know. (P08)

Third, it was suggested that, as well as pictures, line art was another form of visual representation that could be included as a special feature of design-oriented software tools and databases.

> A lot of times I go online and I just search images; and to me, I can search much quicker that way. You know, for me, I see an image that would lead me down a path to give me some more, and then dive in deeper with more descriptive stuff about it. And I think you can apply other things to search engines, not just the images and the text, but maybe something like line art. Maybe just representations with things like line art, search in that direction. (P01)

Therefore, software tools might provide access to visual representations such as computer simulations, photographs and line art, not just to stimulate design ideas, but to support cross-disciplinary communication within BID teams. Furthermore, it could be important for BID tool developers to recognise the other information sources and search practices that users will employ in their work. BID tools should be compatible those other sources and information exchange between them should be supported.

3.3 Orientations to biology

The processes of developing BID ideas illustrate specific orientations to biology that the team members follow in their work, implicitly or explicitly. Below, we discuss three orientations to biology that could be identified in the research participants' accounts: *nature is not perfect*; *environment, interaction and exchange*; and *animals as machines*.

3.3.1 Nature is not perfect: examples of non-optimal solutions

The practitioners claimed that novices can sometimes fall into the trap of assuming that any biological inspiration could result in a useful or optimal product. In contrast, those with years of experience in BID are more likely to realise that nature is not perfect.

> […] this brings up another, I think, weak point in the biomimetics field. I don't know if I'm being overly-sensitive when I say this, but I feel like sometimes people assume that nature has come up with the best solution that anybody can ever invent; and I don't think that's necessarily true whatsoever. You know, a great example of that is airplanes: lift and propulsion are totally decoupled, right? You have the engine, and then you have the wing, right? Whereas, in a bird, they're coupled. The wing that provides lift is also the propulsion source. Well, from an engineering perspective it makes a lot of sense to do the wing and the engine, you know, as separate things. (P13)

The assumption that nature is perfect could sometimes be employed in a simplistic way as a justification for having developed a useful product. Experienced BID practitioners, however, know that the understanding of what works and what does not work in nature, as in engineering, is much more complex than this assumption suggests:

> So, in other words, there is this idea – and I think [a certain BID tool] sort of promotes this a little bit much – that nature is perfect: nature is good, and so anything from nature is going to do the job and do it better. And that's not necessarily the case, and too often engineers use it as a justification. Nature has been in the business of designing things for billions of years, through the process of evolution, and that's not always correct. Often times, what we find in evolution isn't that you necessarily build for the optimal, or the perfect, or… You just deal with what's adequate, what can get you through. Things that are developed have to interact with a variety of systems, and so again they're not going to give you everything that's perfect and such. So, we have to watch this over-emphasis on the idea that nature represents some sort of perfection. (P02)

Software tool developers could respond to this in different ways. The tools might explicitly incorporate and discuss examples of 'non-optimal solutions' in order to assist users in moving beyond the assumption that nature is perfect (should they hold such an assumption or lapse into it). Or, the tools could identify those specific features that are known to be compromised in otherwise efficient systems so that users are not left puzzling over seemingly inefficient details (which might just result from path-dependant development processes). Alternatively, the tools could emphasise where the biological entities that are represented are not well understood in biological science.

> I searched for papers on the genealogy and biology of a [specific insect]. For example, I wanted to know: why is the [specific insect] blue? What biological function does that serve? It was interesting to find that nobody really understands it. There are several theories, but nobody understands why. What evolutionary factor made the wings blue? (P08)

In other cases, the efficacy of a specific feature might be less apparent in the biological entity than in the resulting BID product:

> One interesting thing is that [...] we didn't realize that a single blade is actually really efficient.... That's something that wasn't obvious from the inspiration, [and] that actually turned out to be something really good [useful]. (P06)

Therefore, by including examples of 'non-optimal solutions' in biology, together with case studies when such examples inspired novel products and technologies, software tools could support BID practitioners in developing a more complex understanding of nature.

3.3.2 Environment, interaction and exchange: multiplicity of information content and of representations

A focus on ecologies, rather than just on individual organisms, is another way of employing a more complex understanding of nature in BID projects. One can learn as much from an organism's interaction and exchange with its environment, as from understanding the internal structure and processes of that organism:

> There is a misunderstanding in most of biomimetics, and that is that by understanding bones, or corals, you can design something as good as that. [But...] when you look at a coral, when you look at a human body, you only have half of the answers. The other answer is the environment. And I don't know why biomimetics people miss this, but, you know, all organisms relate to their environment, and they make themselves out of the materials in their environment, right? So you cannot understand how a coral works without understanding the ocean in which it lives. For example, a coral can build its structure, or repair its structure, because of the ions in sea water [...] In any system I would design, you would have to tell me everything about what's available and what are the processes, what are the sources, what are the materials and everything. And that would tell me what my possibilities are, and then I would look for inspiration about how the other organisms survive there and what mechanisms they use. And my solution would be an exchange back and forth with the environment [...]. And if you miss the environment piece, you're just making more machines. I don't care if they're based on the design of something [biological]. You're just making machines. So you can call them mimicking biology, but not really... You're mimicking the results of biology. (P12)

Analogical design tools could support BID practitioners who are interested in understanding a biological system at many different levels, including not just ecological perspectives, but also those that emphasise molecular, cellular and genetic factors. In order for one to develop an understanding of the interactions across these levels several types of information are necessary, such as: an inventory of the physical attributes of the entity; photographs of how the organism behaves; and videos, animations, or flowcharts that show how the process works.

> Again, I view it as you are trying to study two different things. One are processes, and the other are materials/components. But either way, even if it's a component, it will still be a matter of how it interacts with its environment. So, it ultimately comes down to having some sort of an inventory of 'what are the physical attributes of the entity', if there are any involved. […] If I'd think of a physical attribute, this would be a matter of the small amount of data processing, small amount of memory, and constant feedback and iteration with its superiors and its environment. Those would be the physical characteristics; the process strand is another story. So, obviously, you're going to have photographs to build an understanding of 'here is what it looks like in the real world', how it behaves. For anything that is a process, you could have it demonstrated: if it's large enough, it can be shown in a video; or, if not, then some animation, so you would understand the process. In some cases, having a flowchart […] would make people think how this process works. (P03)

Therefore, by providing multiplicity of content, together with a wide range of representations – including visual representations – software tools could support BID practitioners to find inspiration in the ways in which organisms interact with their environments.

3.3.3 Animals as machines: models and catalogues

Sometimes the engineering knowledge employed in BID projects involves applying mechanical principles to living organisms. The research participants coming from engineering backgrounds mentioned these aspects of their work by describing how, in some situations, they tried to calculate the efficiency of animals' movements and actions by using principles and formulas from mechanics. This process of calculation was necessary in order to discover where exactly, in the way an organism worked, laid the novelty that could further inspire the development of an innovative product.

> It will be interesting to take animals and just rate them as machines, like what's the power, what's the efficiency, what's the max speed, what's the weight. You know, that's the type of stuff that I had to do in this project, which would… you know, in the biology papers that's not what they're doing. You know, it was actually kind of tricky what I had to do. There is a guy […] who tested [a biological system] back in the 60s and he did things

> like measure how much pulling force they can exert with their foot [...] But that didn't give me a sense of energy or power, you know. I had to do estimation, saying, 'okay, if they're pulling with this much force and they move down this amount every digging cycle', you know, just from force [multiplied by] distance, then I can get a sense of how much energy they're exerting. (P13)

Analogical design tools could address this issue in a number of ways, such as providing visual representations of movement and actions, together with models that could be used to represent natural systems in new ways:

> If it is all mechanical systems, like mechanical solutions in animals, trying to model it using components that are available in engineering, such as springs, or clutches, or I don't know, dampers... So, trying to abstract the natural system, the animal in these type of terms, to make this link. This link is an aid, and this will allow people to use that in engineering. And because not everyone in engineering might be interested in animals or able to extract those principles, this step, I think, is a key contribution. Another thing that is important I think would be having movies of how animals [...] do the different movements. (P10)

One participant suggested that the information content of software tools could be organized as catalogues consisting of specification sheets of general metrics – such as energy, speed, mass, efficiency – for different organisms. These catalogues would make it easier for BID practitioners to evaluate and compare specific features of a range of organisms.

> You know, on my bookshelf next to me I have these engineering catalogues that I can look through and find parts. I think it's a similar type of catalogue where you can look up: 'Okay, there is a penguin, what's his coefficient of drag? What's his efficiency? What's his lift-to-drag ratio?' You know, like all these things, maybe that would help designers, help engineers to use biologically-inspired things [...] I don't know, these general metrics by which you could evaluate any animal. Hmm... You know, engineers care about power and energy, speed and weight, and efficiency. You know, those categories are really useful. But then I don't know how you compare to other technologies; the engineer would have to do the work to find the other technologies. I think the easiest thing would be to say: 'here's a bunch of animals, here's the power, weight, efficiency, force output, duration of power output', you know. You basically look at it as a machine. I think about it like, if you're shopping for cars, you can get the spec sheet of miles per gallon, power output, gross vehicle weight, zero-to-sixty acceleration time, maximum speed; you know, all these metrics that you can use then to compare other cars. I think if you can do that for animals that would be great. (P13)

The discussion of these three orientations to biology has shown several distinct ways of making connections between the natural world and new technologies. Therefore, it might be challenging, as our research participants pointed out, to find a single way of organizing information that would be relevant and helpful for all BID practitioners, or even for many of them. A variety of approaches would have to be accommodated.

4 Discussion

The participants' reflections on their own professional practice illustrate the complexity and diversity of real-world bio-inspired design activities. The project accounts that they offered combined three important ingredients: (1) people with specific skills and personal traits, such as appreciation of the role that serendipitous encounters can have in providing inspiration, curiosity and interest in a range of domains, and the ability to identify cross-disciplinary connections (2) collaborative work practices across disciplines, where shared understandings of language and shared worldviews can be reached by employing various representations in communication, especially visual representations; (3) specific orientations towards biology, including a questioning approach to the value of biological solutions, a focus on the interactions that organisms have with their environment and a way of viewing those organisms from an engineering perspective. However, there is no single recipe for a successful BID project and these three ingredients were mixed in different ways, resulting in a range of different BID processes. Analogical design support tools have the potential to support individuals and teams in their projects, but for this potential to be realised, such tools should account for the diversity of BID processes.

4.1 Characteristics of BID processes

By reviewing the findings reported above, it is possible to represent the characteristics of the different BID processes associated with each project (see Figure 1). This representation illustrates the variety of approaches followed by the BID practitioners and it can be employed alongside our thematic analysis to gain further insight into how BID projects are conducted in the wild, and where opportunities might lie to provide support. We identify two characteristics of BID processes: the driving issue that initiated the *project start*; and the *process stages* that each project followed.

We identified the project start in relation to the moment when the participant began to work on the problem, or on the solution, that represents the essence of the project. Three types of project starts could be identified from the practitioners' accounts of their work: those that were problem-driven; those that were solution-driven; and those that were theme-driven. The first two types of BID processes are often defined in the literature (Helms, Vattam, & Goel, 2009). However, this division is not always clear-cut, as sometimes problem-

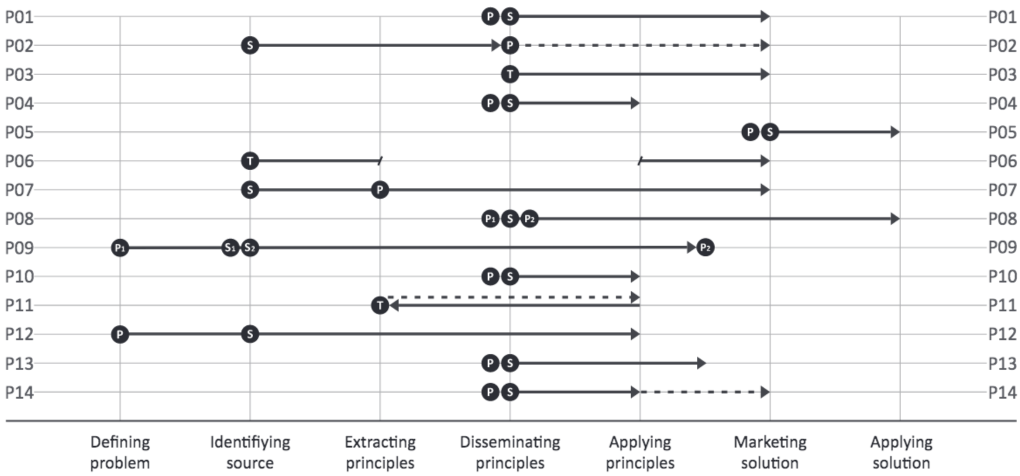

Figure 1 Characteristics of the BID accounts offered by the participants. 'P' denotes problem-driven start; 'S' denotes solution-driven start; 'T' denotes theme-driven start. Consecutive Ps and Ss are used to represent moments when a different solution or a problem is identified on the same topic (P_1, P_2, etc.). Horizontal lines indicate the participants' role(s) in the project; dashed lines indicate that the project continued without the involvement of the expert. The gap in the line for P06 indicates the stages that were skipped during that project. Arrowheads indicate the direction of the process (in the case of P11, a conceptual application inspired by the biological source was used to investigate principles regarding the biological source's behaviour).

driven processes can evolve into solution-driven ones, similar to what Helms and Goel (2012) described as problem-solution co-evolution (also see Dorst & Cross, 2001; Maher & Poon, 1996). This could be observed in our data too, but we also identified what we call theme-driven start. This refers to situations where only a theme or area of study was identified at the project's outset, with no particular problems or solutions in mind. In this more exploratory approach, the practitioners sought out opportunities for chance encounters, which might initiate a new BID project. This shines light on the fact that existing software tools primarily support deliberate search, which comes from either problem-driven or solution-driven orientations. By looking at ways of supporting such exploratory approaches, one could develop a set of software tools that would be more useful to practitioners.

The real-world projects described in this study are more complex and include more stages than those previously described for other contexts. For example, research on BID processes in the classroom has identified four generic stages for BID processes: formulate a problem or search for objectives; search for biological analogues; analysis of a biological system; and transfer (Sartori, Pal, & Chakrabarti, 2010). In contrast, we identified seven distinct stages mentioned by our research participants. Whilst no single participant referred to all of these stages, we include this range because each stage appears at least once in the collected accounts:

1. *Defining problem,* where a problem is set at the beginning, usually as a part of an academic research process.
2. *Identifying source,* where a biological structure or process is identified for study, either because it is seen to answer the identified problem or because of professional curiosity.
3. *Extracting principles*, where the working principles from the inspiration source are researched, or surface features of the source are examined from a design perspective.
4. *Disseminating principles*, where the extracted principles are disseminated — usually through publications.[2] When these publications are accessed by other practitioners, there is a chance that the studied biological source can meet real world problems. Therefore, many of the participants' projects started at this stage.
5. *Applying principles* (to generate a solution), where conceptual applications or prototypes are developed based on the disseminated principles. Some of the BID projects ended with the ideas being incorporated into technologies that could be marketed once they were introduced to an industrial setting; others were on the way to being marketed; while other applications solely served educational purposes.
6. *Marketing solution,* where the solution is targeted at its immediate 'users', whether that is customers (who will buy it) or those who will incorporate it into products.
7. *Applying solution*, where marketed solutions serve as technologies that can be utilized while developing products, for example as materials that can be used in developing other structures.

Not all of the project accounts that we report on here related to all of these stages, as the participants were sometimes only involved for some stages and not others. This potential variation in how and when practitioners engage with the BID process poses challenges BID tool development, because users may approach such tools with very different objectives and very different needs.

4.2 Tool requirements

Based on our findings, we identified several requirements that should be considered while developing an information tool. Some of those requirements overlap with the ones identified in Töre Yargın and Crilly's (2015) review (*abstraction*, *exemplification*, *mode of representation*, *open-endedness*, *multiplicity*, *interactivity*, *transparency*, and *adaptability*), but not all. For example, although they were listed in Töre Yargın and Crilly's review, we here found no strong evidence in the accounts collected here for the requirements of *concision*, *accessibility*, *connectivity*, *shareability*, and *restoration*. Perhaps more interestingly, this study highlights a number of requirements that are absent from those listed by Töre Yargın and Crilly. In particular, our participants raised the need for *cross-disciplinary education support*, *examples of non-optimal solutions*, and *models and catalogues*. Whether originating from this study or not, the various tool requirements can be structured according to the information content that the tool delivers and how the user of the tool interacts with that content. This is all summarised in Figure 2, which represents the relationship between the tool requirements and the research themes discussed in Section 3.

4.2.1 The information content of software tools

Regarding the information content of software tools, the main requirement that emerged was multiplicity. This was the case at all three levels of analysis: the skills set of individuals, practices of interdisciplinary collaboration, and orientations to nature in BID processes. Multiplicity can be delivered by increasing both the breadth and the depth of information that the tool provides. This should include several types of knowledge, such as a good mix of academic and general knowledge that would support individuals' interests in multiple fields. For the purpose of supporting interdisciplinary translation, it was suggested that software tools should include, for each entry, associated key terms from multiple disciplines. Regarding this issue, Shu (2010) and Cheong, Chiu, Shu, Stone, and McAdams (2011) propose a natural language processing approach to enable searching biological texts (such as books and papers) by using engineering terms. This helps to overcome the barrier of terminology difference when searching for relevant analogical sources in biology. Integrating such an approach to BID tool development enables users to familiarize themselves with the language employed in other domains. It would also allow BID tools to support designers in feeding back contributions to biologists, when design-driven enquiry yields new scientific questions or answers. Furthermore, multiplicity of content and of representations – including visual representations such as line art, photography and video simulation – could support a more complex understanding of the biological inspiration source. This could especially be the case for representing processes of interaction and exchange between different levels of the biological entity (e.g. between the organism and its environment).

Whether to focus on either breadth or depth of information seems to be one of the main questions facing those who develop the repositories that analogical design support tools draw from. There are tools that provide breadth of knowledge and that aim to allow experts to search through a variety of sources, such as BioMAPS and Natural Language-based search tools (Cheong & Shu, 2012, pp. 373–382; Shu, 2010). Other tools, such as DANE (Goel et al., 2012), IdeaINSPIRE (Chakrabarti et al., 2005) and AskNature (Deldin & Schuknecht, 2014) focus on depth of information by providing access to well-analysed and curated knowledge. A key step in the progression of BID software tools would be understanding how to identify the optimal

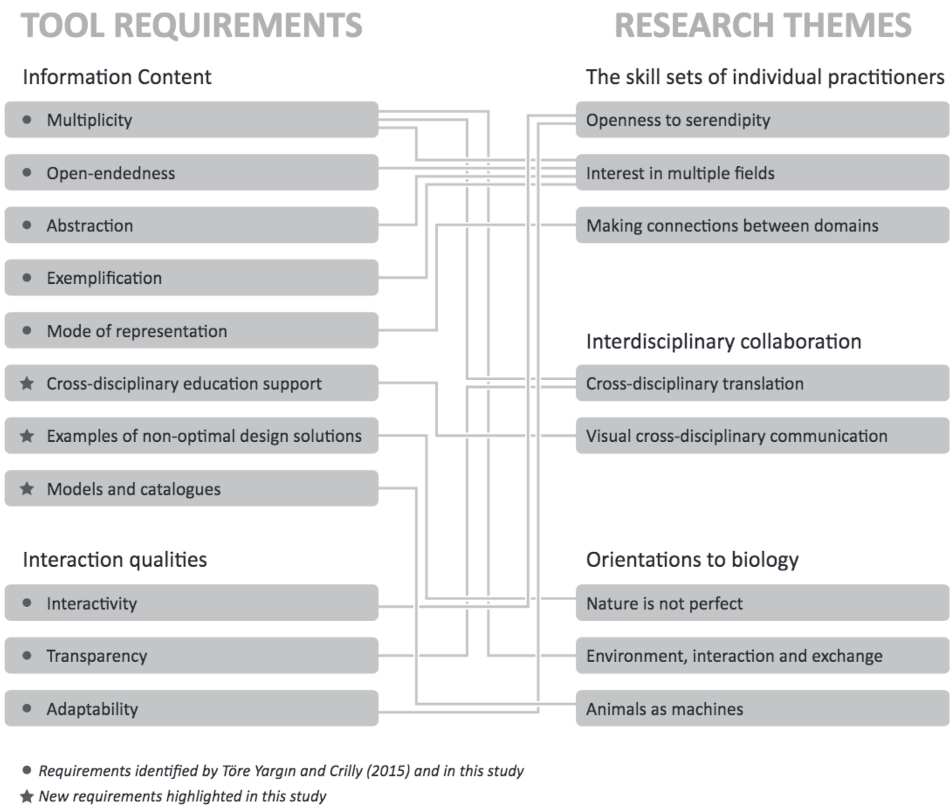

Figure 2 The relationship between tool requirements (those highlighted in this paper and in Töre Yargın and Crilly's (2015) review) and the research themes highlighted in Section 3.

balance of breadth and depth. The technique of mixing general and academic knowledge, which we described above, is one way of moving towards a balance of breadth and depth. Multiplicity of content can support open-ended interpretations. For example, when academic and general knowledge are brought together for cross-fertilization within the same platform, new interpretations of the information are permitted that combine the reader's disciplinary background, the opinions voiced in media stories, and the evidence presented in academic papers. Open-endedness is one of the two most important user requirements identified by Töre Yargın and Crilly (2015) and was highlighted as important in this study also.

A good mix of abstraction and exemplification is important for supporting the BID practitioners' interest in multiple fields. The abstraction of principles of how a biological system functions can be a key strategy for transferring and translating knowledge from biology to engineering. At the same time, a high degree of exemplification supports the situations when practitioners are addressing highly specific research questions which cannot be progressed before finding an exact example. The fixation effect that examples can induce is a critical concern in design generally (Cardoso & Badke-Schaub, 2011; Goldschmidt, 2011; Jansson & Smith, 1991), and it has also been observed in BID specifically (Helms et al., 2009; Mak & Shu, 2008). Abstraction might be important for overcoming this effect (but see Vasconcelos, Cardoso, Sääksjärvi, Chen, & Crilly, 2017), while a high level of exemplification is important for BID questions that are highly specific. Regarding the mode of representation, practitioners considered the display of visuals such as line art, photography and video simulation alongside text to be a very useful way of presenting knowledge. Sometimes visual search is performed to review a wide range of inspiration sources in one glance. Visuals also act as shared representations that enable experts from different domains to see connections and to experience 'lightbulb moments'. Collaboration with people who can visualize how the end product will look, and who are able to employ visual representations in a cross-disciplinary way was generally considered a good work strategy in BID.

The new requirements highlighted by participants include cross-disciplinary education support. This refers to situations when, more than just being used as databases for BID examples, software tools could be employed as part of wider cross-disciplinary educational programs to train individuals in multiple domains that they could then build connections between. It was also suggested that the information content of BID tools should include examples of non-optimal solutions, such as situations when the path-dependant nature of evolutionary change leads to structures that are inefficient (such as the routing of the optic nerve in vertebrates resulting in blind spots). Alternatively, there are instances where biological features that have not been fully understood in biological science have still been built upon in successful BID projects. It is also possible for features that are not necessarily considered to be efficient in the biological world to become inspiration sources for new and efficient products. By including such examples, software tools could support BID practitioners in remaining sceptical of simply mimicking biological solutions. It might encourage them to develop a more sophisticated understanding of the natural world, while highlighting the role that engineers and designers can have in feeding back new knowledge to the biological sciences.

Lastly, the information content of BID tools could be organized as models and catalogues including specification sheets of general metrics — such as energy, speed and mass — that could be employed to evaluate and compare a range of biological systems. This form of organizing information would be specifically useful for engineers and designers in choosing a source of inspiration that looks promising in relation to the parameters that they are interested in.

4.2.2 *The interaction qualities of software tools*

In the literature on creativity support tools it is suggested that interactivity supports exploration by eliciting reciprocity in communication — when the tool 'talks back to the users' (Resnick et al., 2005). However, existing BID tools do not focus much on interactivity, and neither does the analogical design support literature more generally. Our study emphasises that finding inspiration is not only desk-based, and that designers often stumble across or look for different channels that can direct them towards finding serendipitous associations. This is a more exploratory approach to finding inspiration that is not currently supported by existing BID tools which primarily focus on deliberate desk-based search activities. In order to support exploratory search activities that are conducted beyond the desk, tool developers could look into enhancing the interactivity features of BID tools, and the range of platforms they work on (e.g. mobile devices).

Transparency in the interaction with the tool was sought by practitioners in two different ways. First, a transparent, or 'open' system would allow experts from multiple fields to generate input using the language and approaches of their own specialist fields, rather than having the information filtered through the lenses of a single predefined field. Second, the participants were interested in seeing transparency in the way recommendation and reputation systems were invoked to support or legitimate specific pieces of information.

Customisation of the tool for different users (e.g. expert vs. novice) and for different working styles (e.g. systematic approaches vs. inspiration driven styles) can be effective in supporting creativity (Resnick et al., 2005). Such adaptability can be managed manually by the user, or the tool can automatically adjust itself to the user's working style (Avital & Te'eni, 2009; Hewett & DePaul, 2000). This requirement for adaptability was expressed by our research participants in relation to connecting the tool to the personality and the work style of the user. When the search results are adapted to the user's personal traits — such as what type of learner they are — the experience of interacting with the tool comes closer to the ways in which one might browse through their favourite bookshop. The adaptability of BID tools can also be enhanced in order to address different work styles, especially where work-related activities and concerns are more integrated in designers' lives and in their other personal interests.

Lastly, tool adaptability could address problem or solution search at different stages in a BID process. Current BID support tools are adaptable for problem search and for solution search (Goel et al., 2012) and also for different levels of problem definition (Chakrabarti et al., 2005). However, we suggest the tools should support problem and solution search activities across the different BID process stages identified in this study. For example, BID tools could support the brainstorming process of identifying possible solution and problem areas together, they could be employed to find application areas for theoretical principles elicited from a biological source, for finding a new market for an existing solution and for utilizing a marketed solution for a new problem.

4.3 Limitations

This is the first reported empirical study of practitioners' requirements for analogical design support tools. As such, it yields a number of new insights that can inform the development of those tools and also suggests directions for future studies to generate further insights. However, the study also has a number of limitations which should be considered when interpreting the findings and responding to them. Firstly, the sample of participants was relatively small, with just fourteen practitioners contributing to the study. Even this limited sample indicated that a broad range of perspectives and practices exist within BID. Some of that variation might be accounted for in the different levels of expertise that were present, as previous work has shown that novice and expert designers differ in how they identify, process and manipulate information and in how they construct analogies (for a review see Dinar et al., 2015). Secondly, the sample was partially self-selecting. Although the precise population of interest was identified by the researchers, only those practitioners who voluntarily agreed to participate in the study were included, and thus it is plausible that the study over-represents the views of those who are inclined to participate in research or discuss BID processes and BID tools. It is also possible that the study over-emphasises accounts of BID projects that were successful if those were the projects that the participants preferred to discuss. Furthermore, the interviews relied on introspection and recall from the participants and also required them to imagine new tools and scenarios, all of which can be difficult in interview settings.

To address the limitations of the present study, future work in this area might choose to expand on the results reported here by conducting further qualitative enquiry, especially interviews and observations that focus on specific kinds of BID project. Clearly, larger and more diverse samples of participants might be recruited, segmented according to level of expertise and targeting specific kinds of BID projects, including projects that failed in some way. Such work could incorporate interventions in practice, seeing the effect that BID tools have in a range of projects and at the various stages at which they might be used. Feedback on these tools could then be elicited (without requiring excessive recall or imagination), to gain a better understanding of the user requirements that emerged during use on live projects. In particular, it would be interesting to understand if the user requirements that were not highlighted in this study (see Section 4.2) actually are important to practitioners or whether they have been overstated in more theoretical works. Such enquiries could be usefully combined with a range of manipulations to the tools themselves, generating further insights into designers' information and interaction practices. One useful way of collating the results of these studies and identifying opportunities for tool development would be to measure the extent to which the emerging requirements are satisfied by the existing and newly developed tools (e.g. by combining the tool requirements in Figure 2 of this present paper with the visual summary presented in Fu et al., 2014 regarding the current research questions they identified related to BID methods and tools). This might be developed further, by combining such an assessment with an analysis of the parts of the BID process that the tools are used in (e.g. the seven stages identified in this present, the eight steps identified by Fayemi et al., 2017, or some other process description altogether).

5 *Conclusion*

Tools that assist in the construction of analogies can serve designers in some of the most difficult challenges in design: the identification of principles and precedents that are related to (however distantly) the design task under consideration. This is especially so in biologically-inspired design, where acquiring the knowledge required to understand both natural and technical systems is very demanding. For developers striving to provide support tools, there are a number of activities that must be undertaken. They must generate a broad and detailed catalogue of possible sources for designers to draw from; they must determine how that information should be structured and presented; and they must also implement an interface to that information, one which promotes interactions that are engaging and effective. Doing all this without a detailed understanding of the user requirements for such tools is likely to make the development process more difficult and less efficient. In contrast, developing design support tools according to a well-grounded understanding of practitioners' requirements promises to allow the development of more effective tools and also increase uptake. By studying the experiences and preferences of BID practitioners, we hope to have begun the detailed exploration of their requirements in this paper. Conducting further work into these requirements and the relationships between them would develop the foundation upon which analogical design support tools can be developed and deployed, and assist in realizing their potential in design research, practice, and education.

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Notes

1. There are different classification schemes for industrial sectors (e.g. for a comparison in finance research see Bhojraj, Lee, & Oler, 2003). For this study, we adopt Global Industry Classification Standard (GICS), which has four levels of distinction for specifying an industrial sector (Economic Sector/Business Sector/Industry Group/Industry). We here use the last level to indicate the industry or domain at which the BID project was targeted.
2. If the principle extraction was only limited to surface features, this stage was skipped (as in P06).

References

Arlitt, R., O'Halloran, B. M., Novak, J., Stone, R. B., & Tumer, I. Y. (2012). Applying designer feedback to generate requirements for an intuitive biologically inspired design tool. In *ASME 2012 international mechanical engineering congress and exposition* (pp. 35–44). Houston, TX: ASME.

Avital, M., & Te'eni, D. (2009). From generative fit to generative capacity: Exploring an emerging dimension of information systems design and task performance. *Information Systems Journal, 19*(4), 345–367.

Barber, J., Bhatta, S., Goel, A., Jacobson, M., Pearce, M., Penberthy, L., et al. (1992). AskJef: Integration of case-based and multimedia technologies for interface design support. In J. S. Gero (Ed.), *Artificial intelligence in Design'92* (pp. 457–475). Dordrecht: Kluwer.

Bhojraj, S., Lee, C., & Oler, D. K. (2003). What's my line? A comparison of industry classification schemes for capital market research. *Journal of Accounting Research, 41*(5), 745–774.

Bingham, C. B., & Kahl, S. J. (2013). The process of schema emergence: assimilation, deconstruction, unitization and the plurality of analogies. *Academy of Management Journal, 56*(1), 14–34.

Cardoso, C., & Badke-Schaub, P. (2011). Fixation or inspiration: Creative problem solving in design. *The Journal of Creative Behavior, 45*(2), 77–82.

Chakrabarti, A., Sarkar, P., Leelavathamma, B., & Nataraju, B. (2005). A functional representation for aiding biomimetic and artificial inspiration of new ideas. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing, 19*(2), 113–132.

Chan, J., Fu, K., Schunn, C., Cagan, J., Wood, K., & Kotovsky, K. (2011). On the benefits and pitfalls of analogies for innovative design: Ideation performance based on analogical distance, commonness, and modality of examples. *Journal of Mechanical Design, 133*(8), 081004.

Cheong, H., Chiu, I., Shu, L. H., Stone, R. B., & McAdams, D. A. (2011). Biologically meaningful keywords for functional terms of the functional basis. *Journal of Mechanical Design, 133*(2), 021007.

Cheong, H., & Shu, L. H. (2012). Automatic extraction of causally related functions from natural-language text for biomimetic design. In *ASME 2012 international design engineering technical conference & computers and information in engineering conference*. Chicago, IL: ASME.

Christensen, B. T., & Schunn, C. D. (2007). The relationship of analogical distance to analogical function and preinventive structure: The case of engineering design. *Memory & Cognition, 35*(1), 29–38.

Clarke, E. (1978). The neural circulation. The use of analogy in medicine. *Medical History, 22*(3), 291–307.

Dahl, D. W., & Moreau, P. (2002). The influence and value of analogical thinking during new product ideation. *Journal of Marketing Research, 39*(1), 47–60.

Deakin, H., & Wakefield, K. (2014). SKYPE interviewing: Reflections of two PhD researchers. *Qualitative Research, 14*(5), 603–616.
Deldin, J.-M., & Schuknecht, M. (2014). The AskNature database: Enabling solutions in biomimetic design. In A. K. Goel, D. A. McAdams, & R. B. Stone (Eds.), *Biologically inspired design* (pp. 17–27). London: Springer-Verlag.
Dinar, M., Shah, J. J., Cagan, J., Leifer, L., Linsey, J., Smith, S. M., et al. (2015). Empirical studies of designer thinking: Past, present, and future. *Journal of Mechanical Design, 137*(2). 021101–021101-13.
Dorst, K., & Cross, N. (2001). Creativity in the design process: Co-evolution of problem–solution. *Design Studies, 22*(5), 425–437.
Dupin, J. J., & Johsua, S. (1989). Analogies and "modeling analogies" in teaching: Some examples in basic electricity. *Science Education, 73*(2), 207–224.
Enkel, E., & Gassmann, O. (2010). Creative imitation: Exploring the case of cross-industry innovation. *R&D Management, 40*(3), 256–270.
Fayemi, P. E., Wanieck, K., Zollfrank, C., Maranzana, N., & Aoussat, A. (2017). Biomimetics: Process, tools and practice. *Bioinspiration & Biomimetics, 12*(1), 011002.
Fu, K., Moreno, D., Yang, M., & Wood, K. L. (2014). Bio-inspired design: An overview investigating open questions from the broader field of design-by-analogy. *Journal of Mechanical Design, 136*(11), 111102.
Gentner, D. (1989). The mechanisms of analogical learning. In S. Vosniadou, & A. Ortony (Eds.), *Similarity and analogical reasoning* (pp. 199–241). Cambridge, UK: Cambridge University Press.
Glier, M. W., McAdams, D. A., & Linsey, J. S. (2011). Concepts in biomimetic Design: Methods and tools to incorporate into a biomimetic design course. In *ASME 2011 international design engineering technical conference & computers and information in engineering conference* (pp. 655–660). Denver, CO: ASME.
Goel, A. K., McAdams, D. A., & Stone, R. B. (2014). *Biologically inspired Design: Computational methods and tools*. London: Springer-Verlag.
Goel, A. K., Vattam, S., Wiltgen, B., & Helms, M. (2012). Cognitive, collaborative, conceptual and creative—four characteristics of the next generation of knowledge-based CAD systems: A study in biologically inspired design. *Computer-aided Design, 44*(10), 879–900.
Goldschmidt, G. (2011). Avoiding design fixation: Transformation and abstraction in mapping from source to target. *The Journal of Creative Behavior, 45*(2), 92–100.
Hanna, P. (2012). Using internet technologies (such as Skype) as a research medium: A research note. *Qualitative Research, 12*(2), 239–242.
Helms, M. E., & Goel, A. K. (2012). Analogical problem evolution in biologically inspired design. In J. S. Gero (Ed.), *Design computing and cognition '12* (pp. 3–19). College Station, Texas: Springer.
Helms, M., Vattam, S. S., & Goel, A. K. (2009). Biologically inspired design: Process and products. *Design Studies, 30*(5), 606–622.
Herstatt, C., & Kalogerakis, K. (2005). How to use analogies for breakthrough innovations. *International Journal of Innovation and Technology Management, 2*(3), 331–347.
Hewett, T. (2005). Informing the design of computer-based environments to support creativity. *International Journal of Human-Computer Studies, 63*(4), 383–409.
Hewett, T., & DePaul, J. L. (2000). Toward a human centered scientific problem solving environment. In E. N. Houstis, E. Gallopoulos, J. R. Rice, &

R. Bramley (Eds.), *Enabling technologies for computational science* (pp. 79–90). Boston: Kluwer.
Hey, J., Linsey, J., Agogino, A. M., & Wood, K. L. (2008). Analogies and metaphors in creative design. *International Journal of Engineering Education, 24*(2), 283–294.
Holland, J. H. (1986). *Induction: Processes of inference, learning, and discovery. Computational models of cognition and perception*. Cambridge, MA: MIT Press.
Holyoak, K. J., & Thagard, P. (1995). *Mental leaps: Analogy in creative thought. A Bradford book*. Cambridge, MA: MIT Press.
Jansson, D. G., & Smith, S. M. (1991). Design fixation. *Design Studies, 12*(1), 3–11.
Kalogerakis, K., Lüthje, C., & Herstatt, C. (2010). Developing innovations based on analogies: Experience from design and engineering consultants. *Journal of Product Innovation Management, 27*(3), 418–436.
Lepora, N. F., Verschure, P., & Prescott, T. J. (2013). The state of the art in biomimetics. *Bioinspiration & Biomimetics, 8*(1), 13001.
Linsey, J. S., Wood, K. L., & Markman, A. B. (2008). Modality and representation in analogy. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing, 22*(02), 85–100.
Maher, M. L., Balachandran, M., & Zhang, D. M. (1995). *Case-based reasoning in design*. New Jersey: Lawrence Erlbaum.
Maher, M. L., & Poon, J. (1996). Modeling design exploration as co-evolution. *Microcomputers in Civil Engineering, 11*(3), 195–209.
Mak, T. W., & Shu, L. H. (2008). Using descriptions of biological phenomena for idea generation. *Research in Engineering Design, 19*(1), 21–28.
Miles, M. B., & Huberman, A. M. (1994). *Qualitative data analysis: An expanded sourcebook*. Beverly Hills: Sage.
Nagel, J. K., Stone, R. B., & McAdams, D. A. (2010). An engineering-to-biology thesaurus for engineering design. In *ASME 2010 international design engineering technical conference & computers and information in engineering conference*. Montreal, Canada: ASME.
Oppenheimer, R. (1956). Analogy in science. *American Psychologist, 11*(3), 127–135.
O'Connor, H., Madge, C., Shaw, R., & Wellens, J. (2008). Internet-based interviewing. In N. Fielding, R. M. Lee, & G. Blank (Eds.), *The Sage handbook of online research methods* (pp. 271–289). London: Sage Publications.
Pearce, M., Goel, A. K., Kolodner, J. L., Zimring, C., Sentosa, L., & Billington, R. (1992). Case-based design support: A case study in architectural design. *IEEE Expert, 7*(5), 14–20.
Resnick, M., Myers, B., Nakakoji, K., Shneiderman, B., Pausch, R., Selker, T., et al. (2005). Design principles for tools to support creative thinking. In B. Shneiderman, G. Fischer, M. Czerwinski, B. Myers, & M. Resnick (Eds.), *NSF workshop report on creativity support tools* (pp. 25–36). Washington, DC: NSF.
Sartori, J., Pal, U., & Chakrabarti, A. (2010). A methodology for supporting "transfer" in biomimetic design. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing, 24*(4), 483–506.
Shu, L. (2010). A natural-language approach to biomimetic design. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing, 24*(4), 507.
Thomas, D. R. (2006). A general inductive approach for analyzing qualitative evaluation data. *American Journal of Evaluation, 27*(2), 237–246.

Töre Yargın, G., & Crilly, N. (2015). Information and interaction requirements for software tools supporting analogical design. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing, 29*(02), 203–214.
Vandevenne, D., Pieters, T., & Duflou, J. R. (2016). Enhancing novelty with knowledge-based support for Biologically-Inspired Design. *Design Studies, 46*, 152–173.
Vasconcelos, L. A., Cardoso, C. C., Sääksjärvi, M., Chen, C.-C., & Crilly, N. (2017). Inspiration and fixation: The influences of example designs and system properties in idea generation. *Journal of Mechanical Design, 139*(3), 031101.
Vattam, S. S., & Goel, A. K. (2011). Foraging for Inspiration: Understanding and supporting the online information seeking practices of biologically inspired designers. In *ASME 2011 international design engineering technical conference & computers and information in engineering conference* (pp. 177–186). Denver, CO: ASME.
Vosniadou, S., & Ortony, A. (1989). Similarity and analogical reasoning: A synthesis. In S. Vosniadou, & A. Ortony (Eds.), *Similarity and analogical reasoning* (pp. 1–17). Cambridge, UK: Cambridge University Press.
Wanieck, K., Fayemi, P. E., Maranzana, N., Zollfrank, C., & Jacobs, S. (2017). Biomimetics and its tools. *Bioinspired, Biomimetic and Nanobiomaterials, 6*(2), 53–66.