Mahmoud Dinar
Mechanical and Aerospace Engineering,
Arizona State University,
Tempe, AZ 85287
e-mail: mdinar@asu.edu

Jami J. Shah
Mechanical and Aerospace Engineering,
Arizona State University,
Tempe, AZ 85287
e-mail: jami.shah@asu.edu

Jonathan Cagan
Department of Mechanical Engineering,
Carnegie Mellon University,
Pittsburgh, PA 15213
e-mail: jcag@andrew.cmu.edu

Larry Leifer
Department of Mechanical Engineering,
Stanford University,
Stanford, CA 94305
e-mail: larry.leifer@stanford.edu

Julie Linsey
George W. Woodruff
School of Mechanical Engineering,
Georgia Institute of Technology,
Atlanta, GA 30313
e-mail: julie.linsey@me.gatech.edu

Steven M. Smith
Department of Psychology,
Texas A&M University,
College Station, TX 77843
e-mail: stevesmith@tamu.edu

Noe Vargas Hernandez
Department of Mechanical Engineering,
The University of Texas at El Paso,
El Paso, TX 79902
e-mail: nvargas@utep.edu

Empirical Studies of Designer Thinking: Past, Present, and Future

Understanding how designers think is core to advancing design methods, tools, and outcomes. Engineering researchers have effectively turned to cognitive science approaches to studying the engineering design process. Empirical methods used for studying designer thinking have included verbal protocols, case studies, and controlled experiments. Studies have looked at the role of design methods, strategies, tools, environment, experience, and group dynamics. Early empirical studies were casual and exploratory with loosely defined objectives and informal analysis methods. Current studies have become more formal, factor controlled, aiming at hypothesis testing, using statistical design of experiments (DOE) and analysis methods such as analysis of variations (ANOVA). Popular pursuits include comparison of experts and novices, identifying and overcoming fixation, role of analogies, effectiveness of ideation methods, and other various tools. This paper first reviews a snapshot of the different approaches to study designers and their processes. Once the current basis is established, the paper explores directions for future or expanded research in this rich and critical area of designer thinking. A variety of data may be collected, and related to both the process and the outcome (designs). But there are still no standards for designing, collecting and analyzing data, partly due to the lack of cognitive models and theories of designer thinking. Data analysis is tedious and the rate of discoveries has been slow. Future studies may need to develop computer based data collection and automated analyses, which may facilitate collection of massive amounts of data with the potential of rapid advancement of the rate of discoveries and development of designer thinking cognitive models. The purpose of this paper is to provide a roadmap to the vast literature for the benefit of new researchers, and also a retrospective for the community. [DOI: 10.1115/1.4029025]

1 Introduction

Design takes place in people's minds. Even if there are extensive computational tools for analysis and geometric and kinematic representation, the creation of the design itself takes place in people's minds. To create the next generation of design tools that aid in the creation of the concept, the design research community must better understand how designers think so that tools can be aligned with designer thinking and designer efficiency, and effectiveness in the creation process can be enabled.

In this paper, the term "Designer Thinking" is defined as cognitive processes and strategies employed by human designers while working on design problems. As far as we can tell, the earliest empirical studies of designer thinking by engineering researchers began in the early 1980s. The focus of design as a science to study arguably stems from the teachings of Herb Simon in his 1969 book, *The Sciences of the Artificial*, where he devoted a chapter to the science of design [1].

For more than 25 years, design researchers have conducted empirical studies of designers to discover their thinking patterns in design tasks. Popular approaches include the think-aloud method in vitro, and to a lesser extent, in vivo, case studies and controlled experiments. Of late, functional magnetic resonance imaging (fMRI) is being used to correlate cognitive operations with physiological phenomena in the brain. Popular subjects of study have been differences between experts and novices, design fixation, effectiveness of ideation methods, role of sketching, and analogical reasoning. Most studies have used students as subjects while working on design problems constructed specifically for the study. Process data (transcripts) and/or notes, sketches, and calculations may be collected during these exercises. Data collected from these experiments is analyzed manually and there is no standardized framework for analysis. Protocol transcripts are segmented, labeled with ad hoc categories chosen by each research group, and represented in various forms (time plots, sequences, linkographs, etc.). From these representations, various conclusions are drawn. For example, that experts use breadth-first search while novices use depth-first [2,3]; experts quickly identify the most critical issues and are opportunistic, while novices treat everything equally [4]; novices tend to be data gatherers, experts ask for

Contributed by the Design Theory and Methodology Committee of ASME for publication in the Journal of Mechanical Design. Manuscript received November 12, 2013; final manuscript received November 3, 2014; published online November 26, 2014. Assoc. Editor: Janis Terpenny.

information only when needed and they process it immediately [5,6]; example exposure can cause fixation [7–9] while problem reframing [10,11], abstraction [12] and incubation [13,14] can overcome fixation; graphical representations, including design sketches, aid ideation [15,16]. Design outcome has been evaluated using quantity, quality, variety, novelty metrics [17], and its variants [18,19]. The design research community has conducted numerous of such studies involving thousands of students and hundreds of practicing engineers. These studies are very time consuming, both in collecting data and analysis, but we are gradually gaining better insight into designer thinking [20,21]. To speed up the discovery process, new empirical methods are also being pursued.

It is difficult to cover all studies, given the vast amount of literature on these subjects. Instead, this paper provides a sampling of studies in each of the empirical methods, starting with protocol analysis and other types of controlled experiments, including DOE, data collection, and analysis methods and major findings to date. As engineering design is a socio-technical activity, we also include a survey of studies related to designers working in teams. We then turn to more recent studies of design cognition, e.g., neurobiological studies of designers' brains. Finally, we contemplate new avenues in the future of designer thinking research.

It may appear that the paper is biased toward design activities in early design stages, such as problem formulation and concept generation. But this is largely driven by the fact that most of the research has focused on conceptual design. We speculate that this might be because embodiment and detailed design use domain specific technical prescriptive procedures that are well understood, such as kinematics, structural and failure analysis, fluid dynamics and thermal analysis, etc.

2 Protocol Studies

Protocol analysis, borrowed from social sciences, is a common empirical method to study designer thinking. It asks participants to think-aloud, uncovering the thought process through postanalysis. It has been used to study how designer(s) go about performing design tasks by using direct observation (video and audio recordings). The recording is transcribed, segmented, and fragments are coded. It has been used for exploratory studies (hypothesis generation), hypothesis testing, and understanding of particular phenomena (e.g., fixation). Both in vivo and in vitro studies have been conducted with designers working in isolation or collaborating in a team (Fig. 1). Limitations of protocol analysis and when it should be applied in design have also been noted by Chiu and Shu [22] and Cross et al. [23].

Two of the earliest studies of mechanical designers are Ullman et al. [24] and Waldron and Waldron [25]. Both studies were interested in developing a general model of the mechanical design process, and quantifiable measures for its assessment. Ullman et al. asked individuals to work on two simple problems while Waldron and Waldron asked design teams to work on a vehicle with complex mechanisms. As a result, Ullman et al. [24] defined the task-episode-accumulation model. They broke down the transcript into units that could be classified as operations which alter the design state. An episode was defined as a sequence of operators used to accomplish a design task (conceptual design, layout design, catalog selection, etc.). Waldron and Waldron [25] discovered extensive use of biological analogies, experts' bias toward first concepts, and experts' opportunistic approach of quickly identifying and devoting initial focus toward the most critical parts of a design.

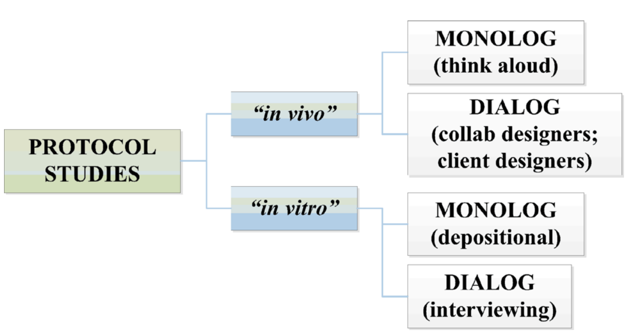

Fig. 1 Classification of protocol study methods

Design Cognitive Processes. A major line of investigation is related to blocks and resolution of impasses in design creativity [6–8,17,18]. One hypothesis in design cognition is that the problem and solution co-evolve [26,27]. Dorst and Cross [10] studied this co-evolution and how it affected creativity. This aspect has also been studied and corroborated by others [28,29]. Other aspects of design cognition studied include: Chan's study on the formation of architectural style [30,31], Liikkanen and Perttula's evaluation of problem decomposition modes [32], and Khaidzir and Lawson's analysis of cognitive actions that take place through conversations between tutors and students [33]. Gero et al. [34] used protocol analysis to study the effect of "structuredness" of three ideation methods on design cognition. They found that the degree of structuredness of a method directly influences the degree of the designers tendency to focus on design goals and requirements.

Role of Sketches and Drawings. Many protocol studies have been accompanied with, or linked to the analysis of the sketches that designers produce during the protocol sessions, especially in the field of architecture. Suwa and Tversky [35] and Suwa et al. [36] asked participants what they thought about their sketches retrospectively and what relations could be found among the underlying cognitive actions. They found that sketches illuminate ideas in early stages of design [35], and in addition to helping as external memory or as a provider of visual cues for association of nonvisual information, sketches help designers to construct design thoughts in a physical setting "on the fly" [36]. Other researchers conducted similar studies on sketches—as external representations of cognitive actions elicited from protocols [37–42].

Novice–Expert Differences. Besides general observations about designers, protocol analysis has been used to find major differences between novice and expert designers. Kavakli and Gero [43] highlighted the differences in novices and experts in their abilities to draw and recognize sketches. Kavakli et al. [44] also found that experts' cognitive actions were organized while novices had many concurrent actions that were hard to categorize. Investigating problem decomposition styles, Ho [4] found that expert designers directly approached the goal state and worked backward for required knowledge, while novices eliminated a problem when they failed to handle it. Ball et al. [45] realized that experts leaned on experiential abstract knowledge and novices relied on case-driven analogies, mainly driven by surface-level cues. Ahmed and Christensen found experts tended to use analogies for predicting component behaviors and problem identification whereas novices tended to transfer geometric properties with evaluating the appropriateness of the analogy [46]. Comparing freshman and senior engineering design students, Atman et al. [47] found that seniors produced higher quality solutions, spent more time solving the problem, considered more alternative solutions and made more transitions between design steps than the freshmen. Moss et al. [48] also found seniors able to reason at a deeper level about function and better understand how components work as a coherent whole than freshmen.

Protocol Methodology Variants. Many variations of protocol analysis have been used, both in how it is conducted and how it is analyzed. Eckersley [49] claimed that he had added to the method by being the first to draw graphs of design problem solving behavior over time across eight variables, utilize computer programs to streamline the encoding and analysis of verbal protocols, use a sample of three encoders, and test experimental hypotheses. Lloyd et al. [50] questioned the ability of the "think-aloud" process to elicit all the information about the very design it sought to reveal, and argued that aspects of designer thinking such as perception and insight were lost in concurrent verbalization. Contrastingly, Gero and Tang [51] saw no major differences between retrospective and concurrent protocol collection. Galle and Béla Kovács [52] introduced an alternative to traditional protocol analysis by trying to replicate the thought processes in going from the original problem statement to a design solution and claimed it to be more effective in the study of real-world design problems. Purcell and Gero [53] reviewed protocol studies with the focus on the use of sketches and how they affected working memory, imagery reinterpretation, and mental synthesis. Besides mechanical engineering, industrial design and architecture, other domains in which protocol studies can be found are electrical design [54,55], systems engineering [56], software engineering [57,58], and textile design [59].

Transcript Coding Methods. Recordings are typically transcribed, annotated with auxiliary information (e.g., gestures, sketches, and doodles), dissected into appropriate fragments and categorized. There are no widely accepted standards for coding protocol data. Researchers have devised various coding schemes suitable for the type of investigation of interest. Table 1 shows excerpts of a protocol transcript coded using two different schemes: function–behavior–structure (F–B–S) [60] and P-map [61]. Apart from coding segments as F, B, or S, the former method also codes requirements as R and identifies the level of abstraction (0—system, 1—input block, 2—PAL block, and 3—output block). P-maps have five major groups (requirements, functions, artifacts, behavior, and issues), each with hierarchically organized subgroups. P-maps are encoded in answer set prolog for data mining.

Sonalkar developed a visual language to code protocols of interpersonal interactions of designers in a team as they occur over the course of time in concept generation sessions [62]. It consists of 12 symbols (Fig. 2). The authors assert "The assignment of symbols is conducted based not on what the expression is from the point of view of the person making it, but on what the expression is taken to be and responded to by others in the team. So what we are modeling is not a series of speaker expressions but rather a series of speaker responses." The letters (A, B, and C) identify the team member. Idea expressions are coded with a different color or line style; thus they could code both ideas and types of interactions in a single representation.

Figure 3 shows three different ways in which the same protocol data may be represented. In theory, these diagrams could be for individuals or aggregated; the particular figures shown happen to be for individuals so that the researcher can see individual differences. Each one shows how the designers' attention moves between different aspects of the problem (requirements, functions, artifact subsolutions, behaviors, and issues) recognized or set aside. The top figure is useful in understanding the extent of additions/changes in each category as a function of time. The middle figure can show task sequence, such as generating a subsolution immediately after identifying a function, or changing the function structure after attempting to generate a subsolution. The bottom figure compares two designers with respect to the distribution of the total time spent on each activity and concurrency of tasks.

Sketch Coding Methods. In some studies, rough sketches created by subjects may be collected to supplement verbal protocol data, or independent of it. There do not, as yet, appear to be any standard methods for analyzing the content and meaning of sketches. Our discussion here is limited to sketch interpretation by human researchers. Sketches may be iconic, conceptual, or representation of physical embodiment of artifacts [63]. In some domains, such as architectural layout, there may be particular ways of depicting elements, such as walls and windows, while in others, such as hydraulics, pneumatics, and electrical circuits,

Table 1 Protocol coding comparison

Fragment	F–B–S	P-maps
But I guess what we need is. some sort of input block there. The PAL, there might be one or two other bits around the PAL, I don't know, and the output block. And that is the fundamental picture of what we are going to have to do.	0S	solution_principle(input_block) physical_embodiment(PAL) solution_principle(output_block) connects(input_block,PAL) connects(PAL,input_block) parameter(number_of_bits_around_PAL)
Darlington driver. if at all possible, an optical darlington driver,	3S	parent_of(output_block,dalington_driver) parent_of(dalington_driver,optical_dalington_driver)
The input block is. really fairly straight forward. opto couplers	1S	parent_of(input_block,opto_couplers)
With of course external pull-ups, I guess so that we can operate on any voltage.	R1S	solution_principle(external_pull_ups) parent_of(input_block,external_pull_ups) function(operate_on_voltage) realizes(input_block,operate_on_voltage) requirement(flexible_input_voltage) fulfills(external_pull_ups, flexible_input_voltage)
That is one of the ideas of putting that input block onto'?'?'?'? not only the safety side but also the flexibility side as well. That is the other reason of course for opticals on that side.	R1F	parameter(location_of_input_block) requirement(safety) manages(location_of_input_block,safety) manages(location_of_input_block,flexible_input_voltage)
My minimum requirement would be for eight inputs minimum. eight inputs sorry eight outputs minimum	R2S	goal(number_of_inputs) goal_target(number_of_inputs,more_than,8) goal(number_of_outputs) goal_target(number_of_outputs,more_than,8)
I happen to know that PALs come in rather strange configurations like twenty fives twenty twos and tens and things like that and if I refer to this book. it should tell me something about the	2S	issue(strange_PAL_config,"PAL's come in strange configurations in number of input outout") relates(strange_PAL_config,PAL) relates(strange_PAL_config,number_of_inputs) relates(strange_PAL_config,number_of_outputs)

Symbols	Name	Example
A	Move	A: I need to buy Legos (at) home. Think about how therapeutic it would be.
? A	Question	A: Where should we start?
B	Hesitation	B: Yeah or not erm (0.8s) there's something erm (1s) when we give (0.4s) yeah.
C	Block	B: Maybe have something which looks like a computer but you can just type your name or do a simple math, a calculator in the shape of a computer kind of. C: Er, but I don't know, I mean, considering the age segment we are targeting 3 to 7 years.
B	Support for move	C: Safe and entertaining (bending forward to write). B: Safe and entertaining, yes.
C	Support for block	A: But that's also, I think that's already done. C: Yeah, its already there. B: Ok.
B C	Overcoming	C: Er, but I don't know, I mean, considering the age segment we are targeting 3 to 7 years. B: So 7 years they go to school, they would learn A, B, C right?
A B	Deflection	B: So when you say we need to divide the age group, but you cannot have like 3, 4, 5. A: No, no of course not, but I mean you might have a few different (concepts).
X	Interruption	B: Should we start generating some concepts now? A: Yeah (interrupted by X) X: 10 min are gone.
C	Yes and	A: What about... if we made a toy that incorporates girls and boys. Its like a house that has a car with it kind of like enables the guys to play with the girls? C: I think that's a good point to have some sort of a educational point in it.
C	Deviation	C: But we need to remember it. C: This is not the buildable room (deviating from previous topic)
A,B	Humor	A: I don't know I probably would have swallowed but (All of them laugh)

Fig. 2 Graphical language for coding (from Ref. [62])

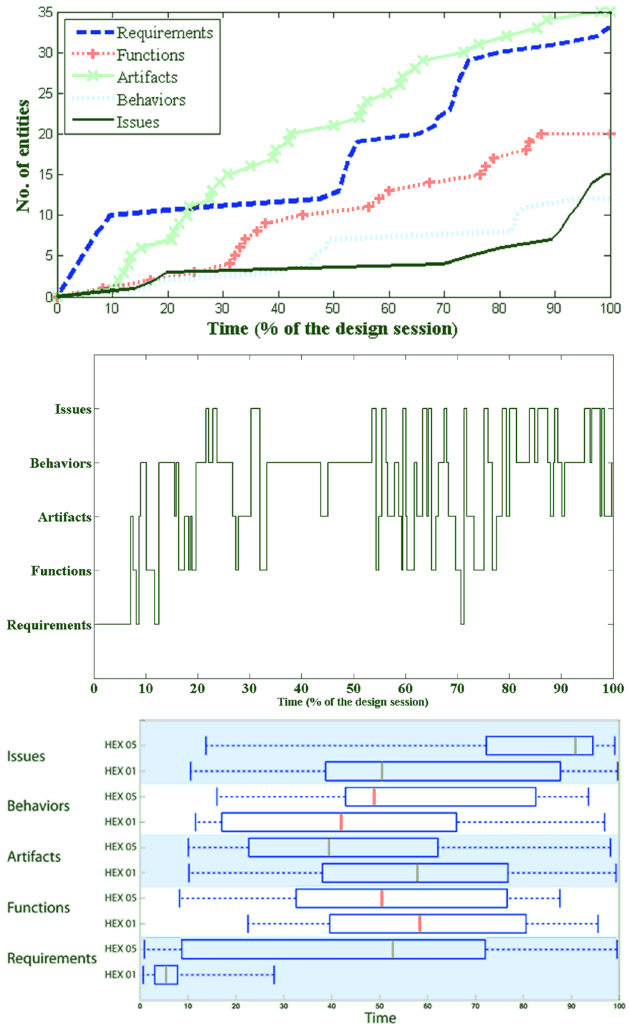

Fig. 3 Alternative representation of protocol data (from Ref. [61])

standard symbols may be used. In interpreting sketches, the quality of drawing is an important issue; poorly drawn sketches or symbols can be misinterpreted. Niemen devised a low-level coding scheme for specific characteristics and relationships of drawings [64]. Do conducted empirical studies of design drawing to determine if it is possible to infer what a designer was thinking by looking at their drawings [65]. Mcfadzean developed a protocol analysis based method for the assessment of conceptual sketching during complex problem solving. It consists of two parts: one captures and timestamps all graphical data from the design session; the other extracts information about the sketches such as lines, shapes, and structures [66]. Kim et al. used tandem analysis of protocol data and sketches to relate personal characteristics and cognitive processes [67]. At the top level, the sketch coding scheme, categorized sketch elements into form, function, human, context, and designer. Form was further subclassified into overall shape and component shape; function into general feature and technical feature (solution realization); human class into physical elements such as user behavior and movement, and mental elements including psychological state; designer class into intent and process management.

Shah conducted experiments to simulate the progression of sketches in the C-sketch method [68]. Sixteen designers were paired up, half from industry. Two design problems were used in the experiment. Each subject generated a solution sketch on their own and then exchanged it with their partner. Subjects then were asked to improve the solution they had received from their respective partners. The procedure for the experiment is shown in Fig. 4. Sketches were photocopied before they were exchanged to trace the development of each idea. The changes made to the sketches were measured by dividing each sketch into "units" that consisted of related drawing units (RDU). Three quantities were measured: retention, modification, and fixation. The retention measure was based on the RDU from the original sketch that survived after changes were made by the second designer (XY ∩ X, YX ∩ Y). Measuring fixation was based on commonality of RDU from each designer's first sketch and changes/additions to the received sketch (XY ∩ Y, YX ∩ X).

3 Controlled Experiments

While protocol analyses study cognitive processes directly, other modes of collecting experimental data have also been

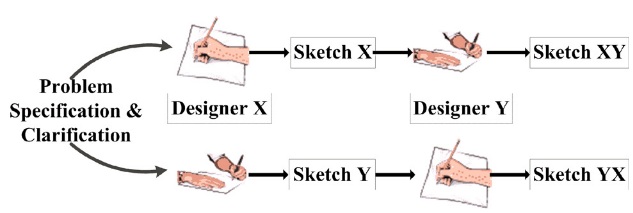

Fig. 4 Experiment fixation experiment procedure [68]

devised. For example, there are studies based on evaluating the outcome of design exercises to indirectly make conclusions about the process. Such studies are suitable for evaluating the effectiveness of various design methods and tools without requiring verbalization during the performance of a task. A claimed advantage of evaluating resulting designs is that engineers are better trained for it than for evaluating cognitive processes. A variety of approaches have been used to study particular cognitive aspects such as design fixation, analogical reasoning, and provocative stimuli.

Cognitive lab experiments, such as those conducted by psychologists, studying human subjects offer greater control and intrinsic validity. Memory and perception experiments can be highly controlled, typically lasting for only a few minutes, allowing large amounts of very specific data to be collected and statistically analyzed. Controlled lab experiments have the advantages of being able to show causality with results that are often generalizable and extensible. Statistically, significant sample sizes can be gathered. These types of experiments are often highly effective when there is either theory, often from other fields, or anecdotal evidence to base hypotheses and research questions on. This type of approach also imposes certain limits, and challenges remain. Generally, it is difficult to run a controlled experiment for more than 3 h and there tends to be significant participant drop out if it is run over multiple sessions. Controlled lab experiments are highly effective for testing hypotheses, but they tend to produce less rich data sets unless this approach is combined with other methods, and it often is. Postexperiment surveys and informal interviews after the experiment are common approaches to collecting richer data sets. Protocol analysis, grounded theory like coding approaches and other qualitative approaches are often applied to provide richer data sets, to explore unexpected results in the experiment, and to add validity to the experimental setup. Controlled cognitive lab experiments [68–73] and quasi-experimental designs [74–76] often with design courses are becoming a well-defined and common approach within engineering design research (although several examples include study of or with the professional designer [8,45,61,77–79]). One of the key challenges for this type of work is metrics. Currently, there is a limited set of defined reliable and valid metrics available with the key exception of work by Shah et al. [17]. In the following paragraphs, we review what we have learned about designer thinking from controlled experiments.

Analogy and Bio-Inspired Design. Design studies demonstrate that bio-inspired design and innovation through analogy are powerful tools for design [77,78,80,81]. Further, controlled experimental studies indicate that the naturalistic studies are likely underestimating the actual frequency of analogy use, since such studies rely on either the designers reporting the use of analogy, or some direct indication of it (e.g., stating a plane is like a bird) [82].

A number of studies in analogy and bio-inspired design are beginning to identify the challenges, cognitive biases, and approaches to assisting engineers. First, it is often difficult to create many solutions based on a single analogue [83–85]. Second, distant domain analogies are ignored unless the design problem is open (unsolved) and unless one has spent time attempting to solve a problem and had difficulty, i.e., an “open goal” [86]. If the analogous information is more distantly related to the problem, it is more likely to be used to solve the problem if it is presented when there is an open design problem to be completed rather than before work has started on the problem [14].

A few approaches for increasing success in design by analogy are being identified. Prior work has consistently shown that presenting two analogues rather than only one increase the rate at which the problem will be solved [83,87–90]. Creating multiple linguistic representations also provides improvement [82,91]. Fu et al. [92] introduced the concept of a “sweet spot” that balances similar or near analogies with distant or far analogies. The sweet spot analogy aids innovation by delivering quality, quantity, and novelty. A computational tool that structures a design repository (such as the U.S. patent database) such that distance from the design problem presents potentially relevant analogies further and further in distance from the design problem can be used to identify those sweet spot analogies [93].

A number of computer tools have been developed for assisting designers in identifying relevant biological analogies (bio-inspired design). Most of these tools use function as the basis of their retrieval. Approaches include leveraging expert curated databases [94–97], BioTRIZ [98], and natural language processing based approaches [99–103]. DANE [96] and idea-inspire [94,95] retrieve biological analogies based on the function or behavior of a device providing both text and images of the results to assist the designer. AskNature [97] lists biologically inspired products and the analogies that inspired their creation with the help of texts and images. AskNature provides both a keyword search and a classification tree to aide retrieval. Expert curated databases are highly effective tools for assisting designers, but require significant resources to create. Natural language processing based approaches leverage existing resources, but are prone to overwhelm designers with an abundance of irrelevant or incomprehensible information. Progress has been made in developing tools to filter out irrelevant results. Much work needs to be done to develop highly effective tools to assist designers.

Design Fixation. Many researchers have identified the fixation effects of example solutions on engineering idea generation [7,8,104–107]. While designers solve open-ended design problems, design fixation plays a counterproductive role, narrowing the solution space where designers search for their ideas and thus reducing creativity. This also reduces the flexibility of designers in choosing novel features for the solutions they generate [8]. Prior studies have shown that designers, when fixated on an example solution, replicate many features from said example in their new designs [7,8,104–106]. These studies use example solutions in pictorial form, such as sketches. Some others have shown that richer pictorial stimuli like the photographs of examples can also induce fixation [108]. Studies investigating the fixating effects of examples in higher fidelity representations are relatively scarce [71,109,110].

A few approaches have been shown to be effective in reducing design fixation. The use of provocative stimuli helps to change the frame of reference for attention, thus helps in the mitigation of fixation [68]. The defixation materials proposed by Linsey et al. [105] consist of alternate representations of the design problem. These materials included a list of analogies, back-of-the envelope calculations and a list of alternate energy sources. They observe that these materials together can help engineering design faculty in mitigating their fixation to a common example that contains several fixating and undesirable features. However, these materials are not equally effective for novice designers, generating ideas under similar conditions [111]. Some recent explorations have shown the potential of physical models in mitigating design fixation [71,109]. As designers build and test the physical models of their designs, they identify the flaws in their designs and mitigate those. This process effectively leads to the mitigation of fixation to features that negatively influence the functionality of their designs. Chrysikou and Weisberg [104] show that design fixation to undesirable example features can be mitigated by warning designers about those features. However, more recent studies have shown that these results do not map to other design problems with comparatively higher levels of complexity [71,112]. Warnings were not enough to prevent fixation.

Evaluation of Design Methods and Tools. Controlled studies have also been used to evaluate design methods and newly developed computational tools [68,73,91,113–116]. Controlled studies and quasi-experimental designs are highly effective for demonstrating the effectives of newly developed computer tools and demonstrating how they compare to the current state of the art [113,117]. Studies have also been used to demonstrate that idea generation methods like C-sketch are more effective than other approaches like a words-only 6-3-5 [68,73,115].

Role of Design Representation. Controlled experiments have also provided insights into the impact that various representations have. Kokotovich and Purcell [15] examined the relationship between creativity and form synthesis in 2D and 3D problems among industrial designers and law students (nondesigners), which showed higher creative responses in 2D problems, and among the industrial designers. Later, Kokotovich [118] examined the helpfulness of a design tool which focused on nonhierarchical representations of problems, e.g., concept maps. Van der Lugt [16] studied the function of sketches in design meetings and found that sketches supported a re-interpretive cycle in the individual thinking process and enhanced access to earlier ideas while they did not support re-interpretation of ideas in group activity. Other experimental studies about sketches and creativity can be found in Refs. [119–122]. Carmel-Gilfilen and Portillo [123] used a different assessment measure, i.e., Perry's measure of intellectual development and the measure of designing.

Other Controlled Studies. Using a graphical user interface (GUI) for parameter setting, Hirschi and Frey [124] experimented with the cognitive load in parametric design and found that design time increased geometrically when the number of parameters went from 2 to 5. Jin and Chusilp [125,126] examined the iteration of cognitive actions for the design of a novel self-powered snowboard, and a routine power transmission under low and high constrains. They found that creative designs require more global iterations as opposed to local loops of routine design problems, and the more constrained the problems are, the less the global iteration. Egan et al. [127] studied the impact of graphical-based tools on solving complex problems, indicating that real time feedback improved consistency and quality as complexity increased.

4 Brain Mapping and Design

fMRI technology is an emerging opportunity to better understand the decision making process of consumers and designers. fMRI images give an indication of relative blood flow in the brain based on the magnetic properties of hemoglobin and how it distorts the magnetic field from a scanner as the field passes through the brain. This property of hemoglobin allows for a measure of how the brain activity in a region of the brain differs across the conditions of the cognitive task being studied. There have been two papers that have addressed fMRI modeling within design to date.

In terms of the designer, Alexiou et al. [128] explored brain activation during design through a pilot study of a simple floor plan layout design task. Their results indicated there is a difference in observed brain activity when solving a well bounded problem versus designing a solution for an open-ended problem.

Sylcott et al. [129] presented different functional attributes and form variations of a car to elicit customer preference through a study run in an fMRI to determine what brain activity might be activated during decision making. Their work demonstrated that the use of fMRI mappings within the customer decision making process is feasible. Subjects were shown a variety of car shapes and functional specifications. Most notable, for conditions where form and function were in conflict, activity was observed in the amygdala, an area in the limbic system linked with emotional experiences and forming memories that have emotional value.

5 Studies of Design Teams

Some of our understanding of designer thinking has come from observing design teams. Tang and Leifer [130] were one of the first researchers to propose video interaction analysis as an observational methodology for studying team design activity. Moreover, in a natural setting, e.g., in a design firm, designing is carried out by teams of designers with different backgrounds in a variety of domains such as mechanical engineering, software design, and industrial design. In another pioneering effort, McCallion and Britton [131] proposed a model to structure team roles in an engineering design team for effective project management. Many of studies of design teams have employed the same methods that we explained earlier, i.e., protocol analysis [132–138] and controlled experiments [16,139].

Fu et al. [9] explored ideation in teams and found that giving a beneficial example to the group is more effective in team coherence (the similarity in mental model of problem/solution representation) and also in terms of quality benefits than a poor example: Teams with a good example had both higher coherence and higher quality outcome than teams with a poor example.

Effective Team Composition. Wilde has reduced design team building to a science through his pioneering work based on Jungian model and Myers–Briggs type indicator (MBTI) personality test [140,141]. He observed that "The success of a collaborative team… depends not only on the combined skill sets of the team members but also on their personalities and ways of approaching and solving problems." The basic idea is to have every team possess among its members the full range of problem solving approaches. While MBTI is a Boolean classification, Wilde quantified them along four axes plus two additional types (centers), as shown in Fig. 5(*a*). He created arithmetic expressions that extracted his types from standard MBTI [140] and assigned threshold values (clear preference, slight preference, and indifference). One can then create composite maps of teams (Fig. 5(*b*)) to see how well equipped a team is for a particular design project.

Wilde reported very positive correlation between team composition and success, although he did not use any control group. He reports that from 1990 to 1999, this method of team contributed strongly to the success of Stanford design teams as judged by the Lincoln "Best of Program" prizes.

Team Dynamics. One of the first statements about the social nature of design was made by Bucciarelli [142] whose ethnographic studies of design projects in engineering firms showed how individuals' views and thoughts form artifacts through encounters of negotiation and agreement. Similarly, Wallace and Hales [143] followed an engineering design project to see the accordance with the systematic design approach of Pahl and Beitz [144] and in the process found unaccounted activities such as socialization, motivation, communication, and reviewing.

Though designing in teams seems to be the dominant practice in real work environments, questioning whether teams are superior to individuals has not eluded researchers. One view was that the social process of design teams had a significant interaction with the technical and the cognitive processes, as noted by Cross and Clayburn [133] pursuant to their workshops on designer thinking [20,23]. Contrarily, Goldschmidt [132] observed no major differences between an individual and a team through a quantitative assessment of design productivity.

Dong et al. [145] found a positive correlation between the semantic similarity of team members' individual mental models of the design process and final design quality, whereby teams with greater semantic coherence produced final designs with higher quality. Wood et al. [146] explored the relationship of individual versus team-based problem solving in design, indicating that collaboration improved consistency in mental models, and early collaboration was the most effective.

To understand designer thinking in teams, several studies have focused on specific representations of design. Goldschmidt [132] used her notation of design moves, linkography, to find how a sequence of critical moves (intensively linked moves) form a critical path. Additionally, Goldschmidt and Tatsa [147] used

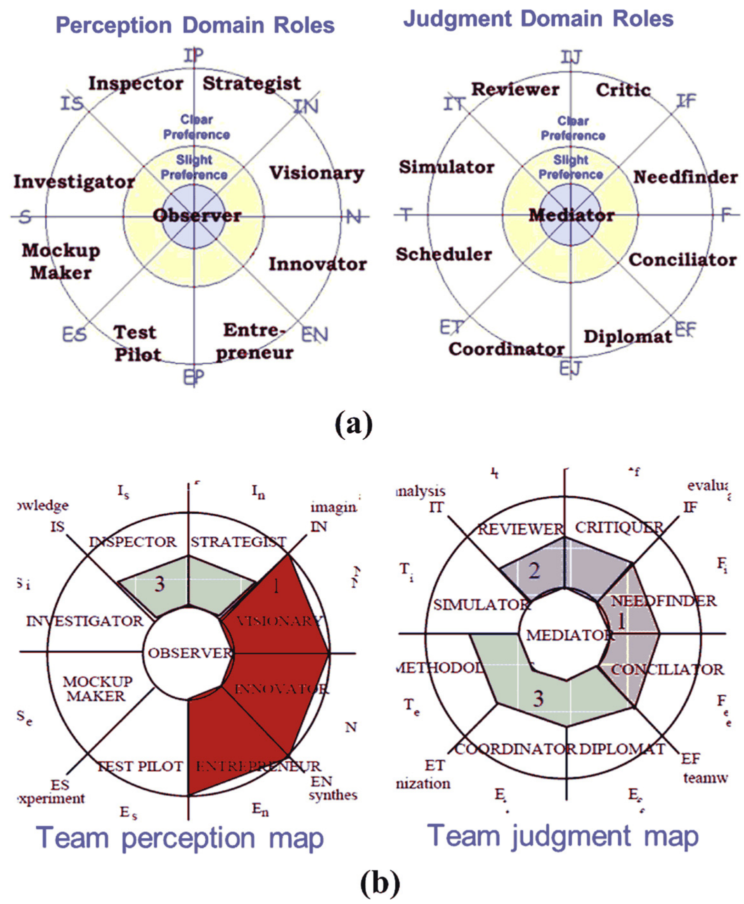

Fig. 5 Wilde's teamology [140,141] (*a*) classification of roles and (*b*) mapping team composite characteristics

linkography to analyze the links between generated concepts and found that highly linked concepts resulted in more effective outcomes. Van der Lugt [16] studied sketches as the external representation which was communicated among members of design groups. As an alternative to visual representations, Eris [148] created a taxonomy of questions that design teams asked during design.

Studied representations were not just external; for example, Valkenburg and Dorst [135] studied reflective practices in design teams. Frankenberger and Auer [134] used a standardized schema for on-line protocol collection to study individuals and teams. Matthews [149] used conversation analysis to study the relationship between brainstorming rules and the social order in design teams during concept generation. Other researchers focused on team communication [136], narration and storytelling [137], and affect in the language of appraisals [138].

A different use of representation was the development of the interaction dynamics notation by Sonalkar et al. [150] for representing moment-to-moment concept generation through interpersonal interactions. They revealed certain patterns of interpersonal interaction such as moments of sustained ideation and sustained disagreement, the occurrence of improvisational responses within idea sequences as well as with transitions between ideas and facts, and the use of ideas to negotiate blocks. Mabogunje et al. [151] also analyzed design conversations in a brainstorming meeting to explain a behavior which they called "resumption." They showed that designers started multiple topics and revisited ideas without completing the topic thread.

6 Other Empirical Approaches

We finish our review of empirical methods of studying engineering design by giving a few examples of other types of empirical studies, interviews, and project-based observations. Paton and Dorst [11] interviewed 15 experienced designers to understand the role of reframing a problem when a customer provides them with a design brief. Participants responded that they found themselves serving one of the roles of "technician," "facilitator," "expert/artist," or "collaborator." They also identified "typicality" of a project with the first two roles, and "innovativeness" with the latter two roles. Petre [152] interviewed 12 engineering consultancies in the UK and U.S. over two years. He described strategies that expert designers used to "get out of the box" of familiar thinking, to identify gaps in existing products, and to go beyond "satisficing." He found that high performance was amplified by a reflective, supportive culture and by highly collaborative multidisciplinary teams, facilitating communication, transfer, and insight.

Long term project-based observations are relatively few in design studies in the past 25 years. Tovey [153] who followed a transportation design project found that sketching would often reveal the combination of analytical and holistic processes that the designer employed. Muller [154] also followed students who designed hand-driven go-karts and espresso machines. Martin and Homer [155] collaborated with a resident student in a company that designed glass cutting machines and saw that the disciplined departure from the apparent problem and the application of creative design techniques generated worthwhile results.

7 Discussion

Cognitive Perspectives on Designer Thinking. Creativity in design is diverse and abundant and creative designs arrive and evolve in a multitude of ways. It is now clear that creative ideas usually involve multiple people, that conscious thought is essential to creative thinking, and that creative cognition is the norm, not the exception [156,157].

Cognitive psychologists often distinguish between cognitive processes, structures, and operations. Cognitive processes refer to simple, but fundamentally important actions carried out in the mind, such as directing attention, recognizing patterns, making decisions, forming concepts, visualizing spaces, or retrieving memories. As such, there is no cognitive process that can be referred to as the creative process. Cognitive structures refer to mental forms such as concepts, schemas, images, semantic networks, and mental models—structures that can be formed, maintained over time, and altered, so as to be useful in the representation of knowledge. The common term "idea" is best thought of as a type of cognitive structure. Cognitive operations are functions carried out via unspecified processes and structures, functions such as combining ideas, computing outcomes, exploring knowledge structures, monitoring thoughts, or generating ideas.

Creative cognition involves a collaboration of cognitive processes operating upon cognitive structures in ways that cope with novel demands, or that meet pre-existing demands in novel ways. This "collaboration" is analogous to the collaboration among members of a team, leaving many degrees of freedom in terms of what any particular collaboration produces. As such, creative cognition can be described as stochastic, rather than deterministic or formulaic, the way that noncreative cognition might solve a math problem or a logic puzzle. That is, although there is no method for assuring that a set of cognitive operations will result in a creative solution, there are nonetheless several operations that commonly contribute to the production or discovery of creative ideas. Some of the cognitive operations that are frequently engaged in creative cognition include divergent thinking, remote association, analogical transfer, visual synthesis, conceptual combination, restructuring, insight, inductive reasoning, incubation, and abstraction [157]. None of these represents a simple cognitive process, but rather they are higher-order cognitive operations.

The history of research in cognitive psychology has shown the necessity of experiments for establishing cause-and-effect relationships. Introspection, even by trained experts, is by definition subjective and biased, and furthermore, it cannot observe unconscious processes. Case studies are worthwhile for observing certain phenomena that are otherwise unobservable (e.g., geniuses or brain-damaged patients), but neither the generality of the conclusions, nor their causal inferences can be assessed. Correlational research can be useful, but it notoriously misattributes causes to factors, with no way for correcting those misattributions. Because the experiment manipulates independent variables, observing their effects on dependent measures while controlling all other factors, it can be used to establish internally valid conclusions about cause and effect.

Yet, it is precisely this necessity for controlling noise variables in experiments that can limit their usefulness in terms of applying their conclusions to real life situations, such as real-world design. That is, in controlling so many potentially relevant factors, a researcher is likely to utilize artificial situations in experiments. Furthermore, by observing effects of individually manipulated variables, one loses the complexity of naturalistic applications, particularly in terms of the possible interactions among many factors. Therefore, it is critically important that research that examines the role of a certain type of cognition on creative design should strive for alignment across all levels of complexity and ecological relevance [158]. Only such an approach can determine, at one extreme, the causal nature of some cognitive factor, and at the other extreme, whether that factor has an impact on real-world creative design.

An example of such an aligned approach in creative conceptual design is studies of fixation effects (see Refs. [159] and [160] and the early discussion on fixation), which shows that exposure to examples can have a constraining effect on creative ideation. At one extreme are highly controlled experiments that show that simply reading words (e.g., ANALOGY) that look similar to solutions to word fragment completion problems (e.g., A_L_ _ GY, solution ALLERGY) causes an involuntary memory block, due to the inappropriate functioning of implicit memory, which brings the wrong solution (ANALOGY) to mind [161]. This basic finding, that examples caused an implicit fixation effect in a highly controlled artificial laboratory experiment, has also been found in creative problem solving [162], creative idea generation in nonexpert students [163], brainstorming [164], creative design in engineering students, and in professional engineering designers. Thus, research studies at all levels of complexity and ecological validity show this design fixation effect, and tie the effect to a simple cognitive mechanism.

Design of Design Experiments. The importance of systematically designed empirical studies cannot be overemphasized. However, in the design research literature, it is not uncommon to find papers that have very tiny sample sizes, little awareness of factors in play and their interactions, and ad hoc metrics in use. While engineers are well versed in designing physical experiments in areas such as solid mechanics, fluids and energy systems, some design researchers appear to be a bit more casual. The DOE method is recognized by the scientific and engineering community as a well-established approach to manage the complexities of empirical studies [165]. In conducting our survey, we particularly looked at how well the empirical study was designed from the outset. That includes a clear problem statement (e.g., hypothesis testing), identification of response variables, controlled and manipulated factors, levels, and ranges, subjects chosen, sample size, type of data collected, statistical analysis of the data, and results (e.g., hypothesis validation).

The choice of experimental design depends on the hypotheses and objectives of each experiment. Two of the most common experimental designs are single comparison and factorial design. One difficulty in designer thinking research is that a design episode can never be replicated exactly, even with the same factors (treatments), subjects (designers), and sample size. Another consideration is individual differences between human subjects; no two subjects will have the same exact background experience going into an experiment, and no individual subject can avoid being changed by participating in an experiment. To control this factor for any subgroup of subjects (e.g., freshmen versus seniors; experts versus novices), a large enough sample size is needed so that the backgrounds get randomized or averaged. The same applies to randomizing teams. Many studies in our field at times appear not to pay sufficient attention to these considerations.

Two typical issues in experimental design are: comparison and interactions. The results of an experiment in a single comparison must be compared against a baseline or benchmark. For simple comparisons, the benchmark could be a "control" group that did not have a factor manipulation, but even in this case, the control group must follow a "neutral" or "no method" design task which may not be an absolute point of reference. For example, if the factor is subject experience, what is the control group to compare against? "No experience" must be clearly defined in this context. With respect to interactions in design creativity experiments, interactions must be planned carefully. For example, with the interaction of frame of reference shifting and incubation [158], which factor is applied first? What is the effect of the order of factors in the responses? In this case, the order of the factors may affect the outcome.

A good conceptual experimental design does not ensure valid results; the execution of the experiment also plays a critical role. The intervention applied to a subject during the experiment can vary from the extensive activities associated with a capstone course, to short training exercises, to a brief video or quick image. Some treatments may require specific instructional methods [166,167], including discipline, culture, and/or concept alignment. Read and Kleiner [168] recommend practicing any training techniques involved, while Burke and Baldwin [169] encourage the use of real-world training tasks. Other researchers have suggested specific criteria by which creativity training can be evaluated and the types of factors that influence their effectiveness can be identified [170,171].

The motivation of subjects must be carefully addressed. The simulated design environment that we create may not have the same consequences for success or failure, thus affecting the ecological validity (i.e., approximation to the real-world) of the experiment.

The design task is also a critical component of the design experiment; it should not be too easy or too difficult to solve given the particular subject sample. Special attention should be placed on the characteristics of the problem (e.g., clarity), as they can affect the way that subjects perceive the problem; too much ambiguity may produce confusion. The knowledge domains required in the design task must match the subjects' background as well.

Design data collected from experiments can vary from verbal/video protocols (words and gestures), to design documents on paper (sketches, notes, and calculations), and even working models. The sequence of representations can capture the development of a design. The assessment of design representations is the foundation for outcome-based studies of design creativity. Various approaches have been developed for the assessment of individual sketches [17,68] and design reports and journals [72,172–175]. Some studies employ expert judges [10,108,176–179]. In social sciences, it is common to see multiple judges so as to remove bias. This requires one to perform inter-rater reliability tests. The use of predefined metrics for outcome assessment helps in the reduction of subjectivity of judges. A variety of metrics have been developed, for example originality, fitness to requirements, fluency, variety, elaboration, problem sensitivity, and ratio of usefulness [176,180]. In this area, at least we find some convergence within the community, that is, use of a common set of metrics and common definitions, albeit with minor tweaks here and there.

Evolutionary Paths: Past and Present. Although the overarching motivation for conducting empirical studies of designer thinking has remained the same, the level of formalism, granularity level, experiment design, and methods have evolved over the years. Consider early studies, such as those by Marples [181] and Bucciarelli [142] that consisted of following industry projects in place by attending meetings, interviews, and examining engineering work. These were completely free of any controls, concluding with informal description of what the individual investigator/consultant observed over a period of time. In the mid-1980s, engineering researchers began using protocol studies (already in use by industrial and architectural design researchers). Examples of these are Ullman et al. [24] and Waldron and Waldron [25]. In both studies, a single designer was used in a think-aloud protocol recording, without any predefined hypothesis or coding method. As other researchers continued along similar lines, several issues with this method became identified [20,23] which led to variations in the method (see Fig. 1). Publication data collected by Jiang and Yen in 2009 found that prior to 1985, there were only a handful of protocol studies of design, all using think-aloud methods [182]. They also found gradual increase in both the variety and number of studies, peaking in the year 2000 but still continuing to be quite popular.

Another aspect of gradual improvement has been in establishing statistical significance of results. This requires systematic DOE, use of control groups, larger sample size, randomization of uncontrolled factors (expertise, personality, and design problem) and use of standard statistical methods.

The lack of standard coding methods and concerns about intercoder disagreement and ability to reproduce results, motivate some to seek alternative methods for collecting data. While protocol analyses study cognitive processes directly, other controlled studies were based on evaluating the outcome of design exercises to indirectly make conclusions about the process. These were described in Sec. 3. While early outcome-based analyses simply looked at whether a method or condition was effective in producing a particular type of result (hypothesis testing), some recent studies are conducting finer grained studies by looking at origins or triggers that contributed to that result. An example is the recent study by Hernandez et al. [183].

In the last five years, we have seen the emergence of brain mapping techniques, such as fMRI (see Sec. 4). There is also a trend toward multilevel [149] or multimodal [184] aligned experiments. Design researchers are collaborating more with cognitive psychologists in order to apply cognitive theories and models to engineering design [14,17,48,69,79,82,105].

Because of the time, it takes to run cognitive studies and the limited number of variables that can be tested, it is promising to consider the use of synergistic use of computer search with cognitive studies. Over the span of this review, computational models have been used to represent and study cognitive methods in the design process [185–187]. Most recently Egan et al. [188] developed a method for synergistic human–machine search strategies, where cognitive studies led to strategies that were implemented by computational agents, that could quickly modify and extensively test those search strategies to derive improved strategies that were then returned to (and tested with) the human designer.

We argued that the field suffers from a lack of formal theories and models of designer thinking. There is a disconnect in the science-practice dichotomy, between proposed theories and prescriptive models (such as Pahl and Beitz's systematic engineering [144]), and professional practice of designing [189]. Jung et al. [190] have proposed a structure for design theory that resolves the gap between the generalizability of theory and situatedness of practice by adding a perception-action dimension to locating design theories in practice. Sonalkar et al. [189] discuss the implications of the dichotomous framing of design theories and suggest that there is no need for a unified design theory, practitioners can contribute to theory building, and more resources should be directed toward building formal theories in collaboration with ethnographic research.

The Way Forward. We reviewed a quarter century of empirical research in theory and methodology of designer thinking. The range of our review spanned the dominant methods of studying designer thinking, i.e., protocol analysis, controlled experiments, and more recently neurobiological studies using fMRI. Additionally, we elaborated on the study of design teams complementing the research on individual designers. The diversity of the undertaken approaches and revealed outcomes shows lack of standards for designing, collecting, and analyzing data. This is partly due to the lack of cognitive models and theories of designer thinking. Moreover, the resource-intensiveness of data analysis, especially in employing protocol studies, limits researchers in conducting studies with sample sizes big enough to show statistically significant and reliable results, and to achieve a higher rate of discoveries. The paper has provided direction and specific methods that researchers seeking to study this field must address.

Future studies may need to develop computer based data collection and automated analyses. Perhaps the application of modern IT techniques could revolutionize how data is collected and analyzed. This may include: the use of smart pens; voice-to-text transcription; computer vision techniques applied to sketch recognition; web based design tools made available to both students and the general public to collect massive amounts of data; use of natural language processing and data mining to automate data analyses; and shared repositories of experimental data, such as protocol transcripts. These have the potential to allow researchers to collect massive amounts of data for exponential advancement of cognitive models.

Acknowledgment

This is a revised version of the paper that was prepared by an ad-hoc committee for the 25th Anniversary DTM conference and presented at a special session in Portland, Oregon in August 2013 (Paper No. DETC2013-13302).

References

[1] Simon, H. A., 1969, *The Sciences of the Artificial*, MIT Press, Cambridge, MA.
[2] Ball, L. J., Evans, J. St. B. T., Dennis, I., and Ormerod, T. C., 1997, "Problem-Solving Strategies and Expertise in Engineering Design," Thinking Reasoning, **3**(4), pp. 247–270.
[3] Cross, N., 2004, "Expertise in Design: An Overview," Des. Stud., **25**(5), pp. 427–441.
[4] Ho, C., 2001, "Some Phenomena of Problem Decomposition Strategy for Design Thinking: Differences Between Novices and Experts," Des. Stud., **22**(1), pp. 27–45.
[5] Atman, C. J., Chimka, J. R., Bursic, K. M., and Nachtmann, H. L., 1999, "A Comparison of Freshman and Senior Engineering Design Processes," Des. Stud., **20**(2), pp. 131–152.
[6] Kim, M. H., Kim, Y. S., Lee, H. S., and Park, J. A., 2007, "An Underlying Cognitive Aspect of Design Creativity: Limited Commitment Mode Control Strategy," Des. Stud., **28**(6), pp. 585–604.
[7] Jansson, D. G., and Smith, S. M., 1991, "Design Fixation," Des. Stud., **12**(1), pp. 3–11.
[8] Purcell, A. T., and Gero, J. S., 1996, "Design and Other Types of Fixation," Des. Stud., **17**(4), pp. 363–383.
[9] Fu, K., Cagan, J., and Kotovsky, K., 2010, "Design Team Convergence: The Influence of Example Solution Quality," ASME J. Mech. Des., **132**(11), p. 111005.
[10] Dorst, K., and Cross, N., 2001, "Creativity in the Design Process: Co-Evolution of Problem–Solution," Des. Stud., **22**(5), pp. 425–437.
[11] Paton, B., and Dorst, K., 2011, "Briefing and Reframing: A Situated Practice," Des. Stud., **32**(6), pp. 573–587.
[12] Ward, T. B., Patterson, M. J., and Sifonis, C. M., 2004, "The Role of Specificity and Abstraction in Creative Idea Generation," Creat. Res. J., **16**(1), pp. 1–9.
[13] Kohn, N., and Smith, S. M., 2009, "Partly Versus Completely Out of Your Mind: Effects of Incubation and Distraction on Resolving Fixation," J. Creat. Behav., **43**(2), pp. 102–118.
[14] Tseng, I., Moss, J., Cagan, J., and Kotovsky, K., 2008, "The Role of Timing and Analogical Similarity in the Stimulation of Idea Generation in Design," Des. Stud., **29**(3), pp. 203–221.
[15] Kokotovich, V., and Purcell, T., 2000, "Mental Synthesis and Creativity in Design: An Experimental Examination," Des. Stud., **21**(5), pp. 437–449.
[16] Van der Lugt, R., 2005, "How Sketching can Affect the Idea Generation Process in Design Group Meetings," Des. Stud., **26**(2), pp. 101–122.
[17] Shah, J. J., Smith, S. M., and Vargas-Hernandez, N., 2003, "Metrics for Measuring Ideation Effectiveness," Des. Stud., **24**(2), pp. 111–134.
[18] Nelson, B. A., Wilson, J. O., Rosen, D., and Yen, J., 2009, "Refined Metrics for Measuring Ideation Effectiveness," Des. Stud., **30**(6), pp. 737–743.
[19] Clevenger, C. M., and Haymaker, J., 2011, "Metrics to Assess Design Guidance," Des. Stud., **32**(5), pp. 431–456.
[20] Cross, N., Dorst, K., and Roozenburg, N., 1992, "Research in Design Thinking," Proceedings of a Workshop Meeting Held at the Faculty of Industrial Design Engineering, Delft University of Technology, The Netherlands, Delft University Press, Delft, The Netherlands, May 29–31, 1991, pp. 3–10.
[21] Dorst, K., 2008, "Design Research: A Revolution Waiting-to-Happen," Des. Stud., **29**(1), pp. 4–11.
[22] Chiu, I., and Shu, L. H., 2010, "Potential Limitations of Verbal Protocols in Design Experiments," ASME Paper No. DETC2010-28675.
[23] Cross, N., Christiaans, H., and Dorst, K., 1996, *Analysing Design Activity*, Wiley, Chichester, UK.
[24] Ullman, D. G., Dietterich, T. G., and Stauffer, L. A., 1988, "A Model of the Mechanical Design Process Based on Empirical Data," Artif. Intell. Eng. Des. Anal. Manuf., **2**(1), pp. 33–52.
[25] Waldron, M. B., and Waldron, K. J., 1988, "A Time Sequence Study of a Complex Mechanical System Design," Des. Stud., **9**(2), pp. 95–106.
[26] Maher, M. L., Poon, J., and Boulanger, S., 1996, "Formalising Design Exploration as Co-Evolution: A Combined Gene Approach," *Advances in Formal Design Methods for CAD: Proceedings of the IFIP WG5.2 Workshop on Formal Design Methods for Computer-Aided Design, June 1995*, J. S. Gero, and F. Sudweeks, eds., Springer, US, pp. 3–30.
[27] Maher, M. L., and Tang, H., 2003, "Co-Evolution as a Computational and Cognitive Model of Design," Res. Eng. Des., **14**(1), pp. 47–63.
[28] Kim, M. J., and Maher, M. L., 2008, "The Impact of Tangible User Interfaces on Spatial Cognition During Collaborative Design," Des. Stud., **29**(3), pp. 222–253.
[29] Lemons, G., Carberry, A., Swan, C., Jarvin, L., and Rogers, C., 2010, "The Benefits of Model Building in Teaching Engineering Design," Des. Stud., **31**(3), pp. 288–309.
[30] Chan, C.-S., 1990, "Cognitive Processes in Architectural Design Problem Solving," Des. Stud., **11**(2), pp. 60–80.
[31] Chan, C.-S., 2001, "An Examination of the Forces That Generate a Style," Des. Stud., **22**(4), pp. 319–346.
[32] Liikkanen, L. A., and Perttula, M., 2009, "Exploring Problem Decomposition in Conceptual Design Among Novice Designers," Des. Stud., **30**(1), pp. 38–59.
[33] Khaidzir, K. A. M., and Lawson, B., 2012, "The Cognitive Construct of Design Conversation," Res. Eng. Des., **24**(4), pp. 331–347.
[34] Gero, J. S., Jiang, H., and Williams, C. B., 2013, "Design Cognition Differences When Using Unstructured, Partially Structured, and Structured Concept Generation Creativity Techniques," Int. J. Des. Creat. Innovation, **1**(4), pp. 196–214.
[35] Suwa, M., and Tversky, B., 1997, "What Do Architects and Students Perceive in Their Design Sketches? A Protocol Analysis," Des. Stud., **18**(4), pp. 385–403.
[36] Suwa, M., Purcell, T., and Gero, J. S., 1998, "Macroscopic Analysis of Design Processes Based on a Scheme for Coding Designers' Cognitive Actions," Des. Stud., **19**(4), pp. 455–483.
[37] Bilda, Z., and Demirkan, H., 2003, "An Insight on Designers' Sketching Activities in Traditional Versus Digital Media," Des. Stud., **24**(1), pp. 27–50.
[38] Bilda, Z., Gero, J. S., and Purcell, T., 2006, "To Sketch or Not to Sketch? That Is the Question," Des. Stud., **27**(5), pp. 587–613.
[39] Cardella, M. E., Atman, C. J., and Adams, R. S., 2006, "Mapping Between Design Activities and External Representations for Engineering Student Designers," Des. Stud., **27**(1), pp. 5–24.
[40] Menezes, A., and Lawson, B., 2006, "How Designers Perceive Sketches," Des. Stud., **27**(5), pp. 571–585.
[41] Rahimian, F. P., and Ibrahim, R., 2011, "Impacts of VR 3D Sketching on Novice Designers' Spatial Cognition in Collaborative Conceptual Architectural Design," Des. Stud., **32**(3), pp. 255–291.
[42] Tang, H. H., Lee, Y. Y., and Gero, J. S., 2011, "Comparing Collaborative Co-Located and Distributed Design Processes in Digital and Traditional Sketching Environments: A Protocol Study Using the Function–Behaviour–Structure Coding Scheme," Des. Stud., **32**(1), pp. 1–29.
[43] Kavakli, M., and Gero, J. S., 2001, "Sketching as Mental Imagery Processing," Des. Stud., **22**(4), pp. 347–364.
[44] Kavakli, M., Sturt, C., and Gero, J. S., 2002, "The Structure of Concurrent Cognitive Actions: A Case Study on Novice and Expert Designers," Des. Stud., **23**(1), pp. 25–40.
[45] Ball, L. J., Ormerod, T. C., and Morley, N. J., 2004, "Spontaneous Analogising in Engineering Design: A Comparative Analysis of Experts and Novices," Des. Stud., **25**(5), pp. 495–508.
[46] Ahmed, S., and Christensen, B. T., 2009, "An In Situ Study of Analogical Reasoning in Novice and Experienced Design Engineers," ASME J. Mech. Des., **131**(11), p. 111004.
[47] Atman, C. J., Cardella, M. E., Turns, J., and Adams, R., 2005, "Comparing Freshman and Senior Engineering Design Processes: An In-Depth Follow-Up Study," Des. Stud., **26**(4), pp. 325–357.
[48] Moss, J., Kotovsky, K., and Cagan, J., 2006, "The Role of Functionality in the Mental Representations of Engineering Students: Some Differences in the Early Stages of Expertise," Cognit. Sci., **30**(1), pp. 65–93.
[49] Eckersley, M., 1988, "The Form of Design Processes: A Protocol Analysis Study," Des. Stud., **9**(2), pp. 86–94.
[50] Lloyd, P., Lawson, B., and Scott, P., 1995, "Can Concurrent Verbalization Reveal Design Cognition?," Des. Stud., **16**(2), pp. 237–259.
[51] Gero, J. S., and Tang, H.-H., 2001, "The Differences Between Retrospective and Concurrent Protocols in Revealing the Process-Oriented Aspects of the Design Process," Des. Stud., **22**(3), pp. 283–295.
[52] Galle, P., and Béla Kovács, L., 1996, "Replication Protocol Analysis: A Method for the Study of Real-World Design Thinking," Des. Stud., **17**(2), pp. 181–200.
[53] Purcell, A. T., and Gero, J. S., 1998, "Drawings and the Design Process: A Review of Protocol Studies in Design and Other Disciplines and Related Research in Cognitive Psychology," Des. Stud., **19**(4), pp. 389–430.
[54] Lloyd, P., and Scott, P., 1994, "Discovering the Design Problem," Des. Stud., **15**(2), pp. 125–140.
[55] Mc Neill, T., Gero, J. S., Warren, J., and Neill, T. M., 1998, "Understanding Conceptual Electronic Design Using Protocol Analysis," Res. Eng. Des., **10**(3), pp. 129–140.
[56] Ennis, C. W., and Gyeszly, S. W., 1991, "Protocol Analysis of the Engineering Systems Design Process," Res. Eng. Des., **3**(1), pp. 15–22.
[57] Davies, S. P., 1995, "Effects of Concurrent Verbalization on Design Problem Solving," Des. Stud., **16**(1), pp. 102–116.
[58] Christiaans, H., and Almendra, R. A., 2010, "Accessing Decision-Making in Software Design," Des. Stud., **31**(6), pp. 641–662.
[59] Seitamaa-Hakkarainen, P., and Hakkarainen, K., 2001, "Composition and Construction in Experts' and Novices' Weaving Design," Des. Stud., **22**(1), pp. 47–66.
[60] Gero, J. S., and Mc Neill, T., 1998, "An Approach to the Analysis of Design Protocols," Des. Stud., **19**(1), pp. 21–61.
[61] Danielescu, A., Dinar, M., Maclellan, C. J., Shah, J. J., and Langley, P., 2012, "The Structure of Creative Design: What Problem Maps Can Tell Us About

Problem Formulation and Creative Designers," ASME Paper No. DETC2012-70325.
[62] Sonalkar, N., Mabogunje, A., and Leifer, L. J., 2013, "Developing a Visual Representation to Characterize Moment-to-Moment Concept Generation in Design Teams," Int. J. Des. Creat. Innovation, **1**(2), pp. 93–108.
[63] Tversky, B., 2002, "What Do Sketches Say About Thinking?," AAAI Spring Symposium, Sketch Understanding Workshop, Stanford, CA, Mar. 25–27, pp. 148–151.
[64] Neiman, B., Gross, M. D., and Do, E. Y.-L., 1999, "Sketches and Their Functions in Early Design. A Retrospective Analysis of a Pavilion House," 4th Design Thinking Research Symposium, DTRS99, Cambridge, MA, Apr. 23–25, pp. 255–266.
[65] Do, E. Y.-L., 2005, "Design Sketches and Sketch Design Tools," Knowl.-Based Syst., **18**(8), pp. 383–405.
[66] McFadzean, J., 1999, "Computational Sketch Analyser (CSA): Extending the Boundaries of Knowledge in CAAD," eCAADe'99: 17th International Conference on Education in Computer Aided Architectural Design Europe, Liverpool, UK, Sept. 15–18, pp. 503–510.
[67] Kim, Y. S., Jin, S. T., and Lee, S. W., 2006, "Design Activities and Personal Creativity Characteristics: A Case Study of Dual Protocol Analysis Using Design Information and Process," ASME Paper No. DETC2006-99654.
[68] Shah, J. J., Vargas-Hernandez, N., Summers, J. D., and Kulkarni, S., 2001, "Collaborative Sketching (C-Sketch)—An Idea Generation Technique for Engineering Design," J. Creat. Behav., **35**(3), pp. 168–198.
[69] Linsey, J. S., Green, M. G., Murphy, J. T., Wood, K. L., and Markman, A. B., 2005, "Collaborating to Success: An Experimental Study of Group Idea Generation Techniques," ASME Paper No. DETC2005-85351.
[70] McKoy, F. L., Vargas-Hernandez, N., Summers, J. D., and Shah, J. J., 2001, "Influence of Design Representation on Effectiveness of Idea Generation," Proceedings of ASME DETC, Pittsburgh, PA, Sept. 9–12, ASME DETC/DTM-21685.
[71] Viswanathan, V. K., and Linsey, J. S., 2012, "Physical Models and Design Thinking: A Study of Functionality, Novelty and Variety of Ideas," ASME J. Mech. Des., **134**(9), p. 091004.
[72] Yang, M. C., and Cham, J. G., 2007, "An Analysis of Sketching Skill and Its Role in Early Stage Engineering Design," ASME J. Mech. Des., **129**(5), pp. 476–482.
[73] Linsey, J. S., Clauss, E. F., Kurtoglu, T., Murphy, J. T., Wood, K. L., and Markman, A. B., 2011, "An Experimental Study of Group Idea Generation Techniques: Understanding the Roles of Idea Representation and Viewing Methods," ASME J. Mech. Des., **133**(3), p. 031008.
[74] Linsey, J. S., and Viswanathan, V. K., 2010, "Innovation Skills for Tomorrow's Sustainable Designers," Int. J. Eng. Educ., **26**(2), pp. 451–461.
[75] Linsey, J., Viswanathan, V. K., and Gadwal, A., 2010, "The Influence of Design Problem Complexity on the Attainment of Design Skills and Student Perceptions," Education Engineering (EDUCON), IEEE, Madrid, Spain, Apr. 14–16, pp. 287–294.
[76] Yang, M. C., and Epstein, D. J., 2005, "A Study of Prototypes, Design Activity, and Design Outcome," Des. Stud., **26**(6), pp. 649–669.
[77] Christensen, B. T., and Schunn, C. D., 2007, "The Relationship of Analogical Distance to Analogical Function and Preinventive Structure: The Case of Engineering Design," Mem. Cognit., **35**(1), pp. 29–38.
[78] Eckert, C., and Stacey, M., 2000, "Sources of Inspiration: A Language of Design," Des. Stud., **21**(5), pp. 523–538.
[79] Fu, K., Chan, J., Schunn, C., Cagan, J., and Kotovsky, K., 2013, "Expert Representation of Design Repository Space: A Comparison to and Validation of Algorithmic Output," Des. Stud., **34**(6), pp. 729–762.
[80] Casakin, H., and Goldschmidt, G., 1999, "Expertise and the Use of Visual Analogy: Implications for Design Education," Des. Stud., **20**(2), pp. 153–175.
[81] Leclercq, P., and Heylighen, A., 2002, "5, 8 Analogies per Hour," *Artificial Intelligence in Design'02*, J. S. Gero, ed., Kluwer Academic Pub, Dordrecht, The Netherlands, pp. 285–303.
[82] Linsey, J. S., Wood, K. L., and Markman, A. B., 2008, "Modality and Representation in Analogy," Artif. Intell. Eng. Des. Anal. Manuf., **22**(2), pp. 85–100.
[83] Gadwal, A., and Linsey, J., 2010, "Exploring Multiple Solutions and Multiple Analogies to Support Innovative Design," *Design Computing and Cognition'10*, Springer, Stuttgart, Germany, pp. 209–227.
[84] Holyoak, K. J., and Thagard, P., 1989, "Analogical Mapping by Constraint Satisfaction," Cognit. Sci., **13**(3), pp. 295–355.
[85] Krawczyk, D. C., Holyoak, K. J., and Hummel, J. E., 2005, "The One-to-One Constraint in Analogical Mapping and Inference," Cognit. Sci., **29**(5), pp. 797–806.
[86] Moss, J., Kotovsky, K., and Cagan, J., 2007, "The Influence of Open Goals on the Acquisition of Problem-Relevant Information," J. Exp. Psychol. Learn. Mem. Cognit., **33**(5), pp. 876–891.
[87] Gick, M. L., and Holyoak, K. J., 1980, "Analogical Problem Solving," Cognit. Psychol., **12**(3), pp. 306–355.
[88] Keane, M. T., 1988, *Analogical Problem Solving*, Wiley, NY.
[89] Markman, A. B., and Gentner, D., 1993, "Structural Alignment During Similarity Comparisons," Cognit. Psychol., **25**(4), p. 431.
[90] Namy, L., and Gentner, D., 2002, "Making a Silk Purse Out of Two Sow's Ears: Young Children's Use of Comparison in Category Learning," Int. J. Exp. Psychol. Gen., **131**(1), pp. 5–15.
[91] Linsey, J. S., Markman, A. B., and Wood, K. L., 2012, "Design by Analogy: A Study of the WordTree Method for Problem Re-Representation," ASME J. Mech. Des., **134**(4), p. 41009.
[92] Fu, K., Chan, J., Cagan, J., Kotovsky, K., Schunn, C., and Wood, K., 2013, "The Meaning of 'Near' and 'Far': The Impact of Structuring Design Databases and the Effect of Distance of Analogy on Design Output," ASME J. Mech. Des., **135**(2), p. 21007.
[93] Fu, K., Cagan, J., Kotovsky, K., and Wood, K., 2013, "Discovering Structure in Design Databases Through Functional and Surface Based Mapping," ASME J. Mech. Des., **135**(3), p. 031006.
[94] Srinivasan, V., and Chakrabarti, A., 2009, "SAPPhIRE–An Approach to Analysis and Synthesis," Proceedings of the International Conference on Engineering Design, Palo Alto, CA, Aug. 24–27, pp. 417–428.
[95] Chakrabarti, A., Sarkar, P., Leelavathamma, B., and Nataraju, B. S., 2005, "A Functional Representation for Aiding Biomimetic and Artificial Inspiration of New Ideas," Artif. Intell. Eng. Des. Anal. Manuf., **19**(2), pp. 113–132.
[96] Vattam, S., Wiltgen, B., Helms, M., Goel, A. K., and Yen, J., 2011, "DANE: Fostering Creativity in and Through Biologically Inspired Design," *Design Creativity 2010*, Springer, London, UK, pp. 115–122.
[97] Ask Nature, "Biomimicry 3.8 Institute," http://www.asknature.org/
[98] Vincent, J. F. V., Bogatyreva, O. A., Bogatyrev, N. R., Bowyer, A., and Pahl, A.-K., 2006, "Biomimetics: Its Practice and Theory," J. R. Soc., Interface, **3**(9), pp. 471–482.
[99] Chiu, I., and Shu, L. H., 2007, "Biomimetic Design Through Natural Language Analysis to Facilitate Cross-Domain Information Retrieval," Artif. Intell. Eng. Des. Anal. Manuf., **21**(1), pp. 45–59.
[100] Nagel, R. L., Midha, P. A., Tinsley, A., Stone, R. B., McAdams, D. A., and Shu, L. H., 2008, "Exploring the Use of Functional Models in Biomimetic Conceptual Design," ASME J. Mech. Des., **130**(12), p. 121102.
[101] Shu, L. H., 2010, "A Natural-Language Approach to Biomimetic Design," Artif. Intell. Eng. Des. Anal. Manuf., **24**(4), p. 507.
[102] Nagel, J. K. S., Stone, R. B., and McAdams, D. A., 2010, "An Engineering-to-Biology Thesaurus for Engineering Design," ASME Paper No. DETC2010-28233.
[103] Glier, M., Mcadams, D. A., and Linsey, J. S., 2013, "An Experimental Investigation of Analogy Formation Using the Engineering-to-Biology Thesaurus," ASME Paper No. DETC2013-13160.
[104] Chrysikou, E. G., and Weisberg, R. W., 2005, "Following the Wrong Footsteps: Fixation Effects of Pictorial Examples in a Design Problem-Solving Task," J. Exp. Psychol. Learn. Mem. Cognit., **31**(5), pp. 1134–1148.
[105] Linsey, J. S., Tseng, I., Fu, K., Cagan, J., Wood, K. L., and Schunn, C. D., 2010, "A Study of Design Fixation, Its Mitigation and Perception in Engineering Design Faculty," ASME J. Mech. Des., **132**(4), p. 041003.
[106] Purcell, A. T., and Gero, J. S., 1992, "Effects of Examples on the Results of a Design Activity," Knowl.-Based Syst., **5**(1), pp. 82–91.
[107] Moss, J., Kotovsky, K., and Cagan, J., 2011, "The Effect of Incidental Hints When Problems Are Suspended Before, During, or After an Impasse," J. Exp. Psychol. Learn. Mem. Cognit., **37**(1), p. 140.
[108] Cardoso, C., and Badke-schaub, P., 2011, "The Influence of Different Pictorial Representations During Idea Generation," J. Creat. Behav., **45**(2), pp. 130–146.
[109] Youmans, R. J., 2011, "The Effects of Physical Prototyping and Group Work on the Reduction of Design Fixation," Des. Stud., **32**(2), pp. 115–138.
[110] Viswanathan, V., and Linsey, J., 2013, "Examining Design Fixation in Engineering Idea Generation: The Role of Example Modality," Int. J. Des. Creat. Innovation, **1**(2), pp. 109–129.
[111] Viswanathan, V. K., and Linsey, J. S., 2013, "Design Fixation and Its Mitigation: A Study on the Role of Expertise," ASME J. Mech. Des., **135**(5), p. 051008.
[112] Viswanathan, V. K., and Linsey, J. S., 2013, "Mitigation of Design Fixation in Engineering Idea Generation: A Study on the Role of Defixation Instructions," International Conference on Research into Design, Chennai, India, Jan. 7–9, IcORD'13, Springer, India, pp. 113–124.
[113] English, K., Naim, A., Lewis, K., Schmidt, S., Viswanathan, V. K., Linsey, J. S., Mcadams, D. A., Bishop, B., Campbell, M. I., Poppa, K., Stone, R. B., and Orsborn, S., 2010, "Impacting Designer Creativity Through IT-Enabled Concept Generation," ASME J. Comput. Inf. Sci. Eng., **10**(3), pp. 31001–31007.
[114] Kurtoglu, T., Campbell, M. I., and Linsey, J. S., 2009, "An Experimental Study on the Effects of a Computational Design Tool on Concept Generation," Des. Stud., **30**(6), pp. 676–703.
[115] Shah, J. J., 1998, "Experimental Investigation of Progressive Idea Generation Techniques in Engineering Design," Proceedings of ASME DETC, Atlanta, GA, Sept. 13–16, pp. 1–15.
[116] White, C., Talley, A., Jensen, D., Wood, K. L., Szmerekovsky, A., and Crawford, R., 2010, "From Brainstorming to C-Sketch to Principles of Historical Innovators: Ideation Techniques to Enhance Student Creativity," ASEE Annual Conference, Louisville, KY, June 20–23, pp. 12–25.
[117] Oriakhi, E., Linsey, J. S., and Peng, X., 2011, "Design-by-Analogy Using the WordTree Method and an Automated WordTree Generating Tool," Proceedings of the International Conference on Engineering Design, Copenhagen, Denmark, Aug. 15–19, pp. 394–403.
[118] Kokotovich, V., 2008, "Problem Analysis and Thinking Tools: An Empirical Study of Non-Hierarchical Mind Mapping," Des. Stud., **29**(1), pp. 49–69.
[119] Goldschmidt, G., and Smolkov, M., 2006, "Variances in the Impact of Visual Stimuli on Design Problem Solving Performance," Des. Stud., **27**(5), pp. 549–569.
[120] Huang, Y., 2008, "Investigating the Cognitive Behavior of Generating Idea Sketches Through Neural Network Systems," Des. Stud., **29**(1), pp. 70–92.
[121] Tovey, M., Porter, S., and Newman, R., 2003, "Sketching, Concept Development and Automotive Design," Des. Stud., **24**(2), pp. 135–153.

[122] Bilda, Z., and Gero, J. S., 2007, "The Impact of Working Memory Limitations on the Design Process During Conceptualization," Des. Stud., **28**(4), pp. 343–367.
[123] Carmel-Gilfilen, C., and Portillo, M., 2012, "Where What's in Common Mediates Disciplinary Diversity in Design Students: A Shared Pathway of Intellectual Development," Des. Stud., **33**(3), pp. 237–261.
[124] Hirschi, N. W., and Frey, D. D., 2002, "Cognition and Complexity: An Experiment on the Effect of Coupling in Parameter Design," Res. Eng. Des., **13**(3), pp. 123–131.
[125] Jin, Y., and Chusilp, P., 2006, "Study of Mental Iteration in Different Design Situations," Des. Stud., **27**(1), pp. 25–55.
[126] Chusilp, P., and Jin, Y., 2006, "Impact of Mental Iteration on Concept Generation," ASME J. Mech. Des., **128**(1), pp. 14–25.
[127] Egan, P., Cagan, J., Schunn, C. D., and LeDuc, P., 2013, "Utilizing Emergent Levels to Facilitate Complex Systems Design: Demonstrated in a Synthetic Biology Domain," ASME Paper No. DETC2013-12072.
[128] Alexiou, K., Zamenopoulos, T., Johnson, J. H., and Gilbert, S. J., 2009, "Exploring the Neurological Basis of Design Cognition Using Brain Imaging: Some Preliminary Results," Des. Stud., **30**(6), pp. 623–647.
[129] Sylcott, B. J., Cagan, J., and Tabibnia, G., 2011, "Understanding of Emotions and Reasoning During Consumer Tradeoff Between Function and Aesthetics in Product Design," ASME Paper No. DETC2011-48173.
[130] Tang, J. C., and Leifer, L. J., 1991, "An Observational Methodology for Studying Group Design Activity," Res. Eng. Des., **2**(4), pp. 209–219.
[131] McCallion, H., and Britton, G. A., 1991, "Effective Management of 'Intellectual'Teams With Specific Reference to Design," J. Eng. Des., **2**(1), pp. 45–53.
[132] Goldschmidt, G., 1995, "The Designer as a Team of One," Des. Stud., **16**(2), pp. 189–209.
[133] Cross, N., and Clayburn Cross, A., 1995, "Observations of Teamwork and Social Processes in Design," Des. Stud., **16**(2), pp. 143–170.
[134] Frankenberger, E., and Auer, P., 1997, "Standardized Observation of Team-Work in Design," Res. Eng. Des., **9**(1), pp. 1–9.
[135] Valkenburg, R., and Dorst, K., 1998, "The Reflective Practice of Design Teams," Des. Stud., **19**(3), pp. 249–271.
[136] Stempfle, J., and Badke-Schaub, P., 2002, "Thinking in Design Teams—An Analysis of Team Communication," Des. Stud., **23**(5), pp. 473–496.
[137] Turner, S., and Turner, P., 2003, "Telling Tales: Understanding the Role of Narrative in the Design of Taxonomic Software," Des. Stud., **24**(6), pp. 537–547.
[138] Dong, A., Kleinsmann, M., and Valkenburg, R., 2009, "Affect-in-Cognition Through the Language of Appraisals," Des. Stud., **30**(2), pp. 138–153.
[139] Smith, R. P., and Leong, A., 1998, "An Observational Study of Design Team Process: A Comparison of Student and Professional Engineers," ASME J. Mech. Des., **120**(4), pp. 636–642.
[140] Wilde, D. J., 1999, "Design Team Role," Proceedings of ASME DETC, Las Vegas, NV, Sept. 12–16, ASME Paper No. DETC/DTM-8774.
[141] Wilde, D. J., 2009, *Teamology: The Construction and Organization of Effective Teams*, Springer, London, UK.
[142] Bucciarelli, L. L., 1984, "Reflective Practice in Engineering Design," Des. Stud., **5**(3), pp. 185–190.
[143] Wallace, K. M., and Hales, C., 1987, "Detailed Analysis of an Engineering Design Project," Proceedings of the International Conference on Engineering Design, Boston, MA, Aug. 17–20, pp. 94–101.
[144] Pahl, G., and Beitz, W., 1996, *Engineering Design: A Systematic Approach*, Springer, London, UK.
[145] Dong, A., Hill, A. W., and Agogino, A. M., 2004, "A Document Analysis Method for Characterizing Design Team Performance," ASME J. Mech. Des., **126**(3), pp. 378–385.
[146] Wood, M., Chen, P., Fu, K., Cagan, J., and Kotovsky, K., 2012, "The Role of Design Team Interaction Structure on Individual and Shared Mental Models," *Design Computing and Cognition'12*, Springer, College Station, TX.
[147] Goldschmidt, G., and Tatsa, D., 2005, "How Good are Good Ideas? Correlates of Design Creativity," Des. Stud., **26**(6), pp. 593–611.
[148] Eris, O., 2004, *Effective Inquiry for Innovative Engineering Design*, Kluwer Academic Publishers, Boston, MA.
[149] Matthews, B., 2009, "Intersections of Brainstorming Rules and Social Order," CoDesign, **5**(1), pp. 65–76.
[150] Sonalkar, N. S., Mabogunje, A. O., and Leifer, L. J., 2012, "A Visual Representation to Characterize Moment to Moment Concept Generation in Design Teams," Proceedings of the 2nd International Conference on Design Creativity (ICDC2012), Glasgow, UK, Sept. 18–20, Vol. 1, pp. 199–210.
[151] Mabogunje, A., Eris, O., Sonalkar, N., Jung, M., and Leifer, L. J., 2009, "Spider Webbing: A Paradigm for Engineering Design Conversations During Concept Generation," *About Designing: Analysing Design Meetings*, J. McDonnell, and P. Llyod, eds., Taylor & Francis, London, UK, pp. 49–65.
[152] Petre, M., 2004, "How Expert Engineering Teams Use Disciplines of Innovation," Des. Stud., **25**(5), pp. 477–493.
[153] Tovey, M., 1986, "Thinking Styles and Modelling Systems," Des. Stud., **7**(1), pp. 20–30.
[154] Muller, W., 1989, "Design Discipline and the Significance of Visuo-Spatial Thinking," Des. Stud., **10**(1), pp. 12–23.
[155] Martin, P., and Homer, G. S., 1986, "The Creative Design Philosophy Applied to the Design of Process Plant," Des. Stud., **7**(4), pp. 216–227.
[156] Finke, R. A., Ward, T. B., and Smith, S. M., 1992, *Creative Cognition: Theory, Research, and Applications*, MIT press, Cambridge, MA.
[157] Smith, S. M., and Ward, T. B., 2012, "Cognition and the Creation of Ideas," *Oxford Handbook of Thinking and Reasoning*, K. J. Holyoak, and R. Morrison, eds., Oxford University Press, Oxford, UK, pp. 456–474.
[158] Hernandez, N. V., Shah, J. J., and Smith, S. M., 2010, "Understanding Design Ideation Mechanisms Through Multilevel Aligned Empirical Studies," Des. Stud., **31**(4), pp. 382–410.
[159] Smith, S. M., 1995, "Fixation, Incubation, and Insight in Memory, Problem Solving, and Creativity," *The Creative Cognition Approach*, S. M. Smith, T. B. Ward, and R. A. Finke, eds., MIT Press, Cambridge, MA, pp. 135–155.
[160] Smith, S. M., 2003, "The Constraining Effects of Initial Ideas," *Group Creativity: Innovation Through Collaboration*, P. Paulus, and B. Nijstad, eds., Oxford University Press, New York, pp. 15–31.
[161] Smith, S. M., and Tindell, D. R., 1997, "Memory Blocks in Word Fragment Completion Caused by Involuntary Retrieval of Orthographically Related Primes," J. Exp. Psychol. Learn. Mem. Cognit., **23**(2), pp. 355–370.
[162] Smith, S. M., and Blankenship, S. E., 1991, "Incubation and the Persistence of Fixation in Problem Solving," Am. J. Psychol., **104**(1), pp. 61–87.
[163] Smith, S. M., Ward, T. B., and Schumacher, J. S., 1993, "Constraining Effects of Examples in a Creative Generation Task," Mem. Cognit., **21**(6), pp. 837–845.
[164] Kohn, N. W., and Smith, S. M., 2010, "Collaborative Fixation: Effects of Others' Ideas on Brainstorming," Appl. Cognit. Psychol., **25**(3), pp. 359–371.
[165] Montgomery, D. C., 2009, *Design and Analysis of Experiments*, Wiley, Hoboken, NJ.
[166] Davis, B. G., 1993, *Tools for Teaching*, Jossey-Bass, San Francisco, CA.
[167] Wilen, W. W., and Phillips, J. A., 1995, "Teaching Critical Thinking: A Metacognitive Approach," Soc. Educ., **59**(3), p. 135.
[168] Read, C. W., and Kleiner, B. H., 1996, "Which Training Methods are Effective?," Manage. Dev. Rev., **9**(2), pp. 24–29.
[169] Burke, L. A., and Baldwin, T. T., 1999, "Workforce Training Transfer: A Study of the Effect of Relapse Prevention Training and Transfer Climate," Hum. Resour. Manage., **38**(3), pp. 227–241.
[170] Amabile, T., 1988, "A Model of Creativity and Innovation in Organizations," *Research in Organizational Behavior*, B. M. Staw, and L. L. Cummings, eds., JAI Press, Greenwich, CT, pp. 123–167.
[171] Sternberg, R. J., and Lubart, T. I., 1996, "Investing in Creativity," Am. Psychol., **51**(7), pp. 677–688.
[172] Westmoreland, S., Ruocco, A., and Schmidt, L., 2011, "Analysis of Capstone Design Reports: Visual Representations," ASME J. Mech. Des., **133**(5), p. 051010.
[173] Westmoreland, S., and Schmidt, L. C., 2010, "What Engineering Student Designers Leave Behind: Developing a Cognitive Coding Scheme for Student Design Journals," Proceedings of the ASME IMECE, Vancouver, BC, Canada, Nov. 12–18, pp. 249–256.
[174] Lau, K., Oehlberg, L., and Agogino, A. M., 2009, "Sketching in Design Journals: An Analysis of Visual Representations in the Product Design Process," 63rd Annual ASEE/EDGD Mid-Year Conference, Berkeley, CA, Jan. 4–7, pp. 23–28.
[175] McGown, A., Green, G., and Rodgers, P. A., 1998, "Visible Ideas: Information Patterns of Conceptual Sketch Activity," Des. Stud., **19**(4), pp. 431–453.
[176] Tate, D., Agarwal, A., and Zhang, L., 2009, "Assessing Design Methods for Functional Representation and Concept Generation: Strategies and Preliminary Results," Proceedings of the International Conference on Engineering Design, Stanford, CA, Aug. 24–27, pp. 441–452.
[177] Cham, J. G., and Yang, M. C., 2005, "Does Sketching Skill Relate to Good Design?," ASME Paper No. DETC2005-85499.
[178] Chiu, I., and Shu, L. H., 2008, "Effects of Dichotomous Lexical Stimuli in Concept Generation," ASME Paper No. DETC2008-49372.
[179] Smith, G., Richardson, J., Summers, J. D., and Mocko, G. M., 2012, "Concept Exploration Through Morphological Charts: An Experimental Study," ASME J. Mech. Des., **134**(5), p. 51004.
[180] Kim, Y. S., Kim, M. J., and Jin, S. T., 2005, "Cognitive Characteristics and Design Creativity: An Experimental Study," ASME Paper No. DETC2005-85520.
[181] Marples, D. L., 1961, "The Decisions of Engineering Design," IRE Trans. Eng. Manage., **EM-8**(2), pp. 55–71.
[182] Jiang, H., and Yen, C. C., 2009, "Protocol Analysis in Design Research: A Review," International Association of Societies of Design Research (IASDR) Conference, Seoul, South Korea, Oct. 18–22, pp. 147–156.
[183] Hernandez, N. V., Schmidt, L. C., and Okudan, G. E., 2013, "Systematic Ideation Effectiveness Study of TRIZ," ASME J. Mech. Des., **135**(10), p. 101009.
[184] Steinert, M., and Jablokow, K., 2013, "Triangulating Front End Engineering Design Activities With Physiology Data and Psychological Preferences," Proceedings of the 19th International Conference on Engineering Design (ICED13), Design for Harmonies, Seoul, South Korea, Aug. 19–22, Vol. 7: Human Behaviour in Design, pp. 109–118.
[185] Cagan, J., and Kotovsky, K., 1997, "Simulated Annealing and the Generation of the Objective Function: A Model of Learning During Problem Solving," Comput. Intell., **13**(4), pp. 534–581.
[186] Campbell, M. I., Cagan, J., and Kotovsky, K., 1999, "A-Design: An Agent-Based Approach to Conceptual Design in a Dynamic Environment," Res. Eng. Des., **11**(3), pp. 172–192.

[187] Campbell, M. I., Cagan, J., and Kotovsky, K., 2000, "Agent-Based Synthesis of Electromechanical Design Configurations," ASME J. Mech. Des., **122**(1), pp. 61–69.

[188] Egan, P., Cagan, J., Schunn, C. D., and LeDuc, P., 2014, "Cognitive-Based Search Strategies for Complex Bio-Nanotechnology Design Derived Through Symbiotic Human and Agent-Based Approaches," Proceedings of ASME DETC, Buffalo, NY, Aug. 17–20, ASME Paper No. DETC2014-34714.

[189] Sonalkar, N., Jung, M., Mabogunje, A., and Leifer, L., 2014, "A Structure for Design Theory," *An Anthology of Theories and Models of Design*, A. Chakrabarti, and L. T. M. Blessing, eds., Springer, London, UK, pp. 67–81.

[190] Jung, M., Sonalkar, N., Mabogunje, A., Banerjee, B., Lande, M., Han, C., and Leifer, L. J., 2010, "Designing Perception-Action Theories: Theory-Building for Design Practice," Proceedings of the Eighth Design Thinking Research Symposium, Sydney, Australia, Oct. 19–20, pp. 233–242.