Physical Design Tools Support and Hinder Innovative Engineering Design

Jooyoung Jang
e-mail: joj15@pitt.edu

Christian D. Schunn
e-mail: schunn@pitt.edu

Learning Research and Development Center,
University of Pittsburgh,
Pittsburgh, PA 15260

Engineers use various physical tools (e.g., computers, smart boards, notes, and prototypes) to support their design work. To understand cognitive processes underlying the innovative design process and to reveal the characteristics of innovation-supporting environments, we examined the pattern of tool use in 43 interdisciplinary engineering design teams enrolled in a full-semester product realization course. Teams worked all semester on a single project, with each team being assigned a different industry-sponsored project. Group meetings were video-recorded. Team success was measured in terms of meeting client requirements, and groups were divided into high, medium, and low success. Successful teams (i.e., high and medium success groups) were found to use a smart board and physical prototypes consistently more often throughout the design process, whereas unsuccessful teams (i.e., low success group) used a computer, laptop, and paper notes more often. Particularly, late adoption of physical prototypes was a key characteristic of unsuccessful teams. [DOI: 10.1115/1.4005651]

Keywords: *design tools, analogies, mental simulation, engineering design*

1 Introduction

Designers use various tools (e.g., computers, smart boards, notes, and rapid prototyping facilities) and the artifacts that these tools produce (e.g., conceptual models, computer aided design (CAD) visualizations, sketches, and physical prototypes) to achieve successful design. As Gero [1] argued, design takes place in "the context within which the designer operates and the context produced by the developing design itself." This context is complex; it is unlikely that there can be a single tool or artifact that strongly supports design processes from start to end, largely because each tool differentially supports and hinders designers' cognitive (e.g., analogy and mental simulation) and social (e.g., shared mental models and task conflict) processes. Although not a matter of absolutes, various levels of different tool use could elicit different levels of innovation or success for the design team. This is our focal research question: how does relative design tool and artifact use during design relate to design team innovation?

This paper will focus upon establishing a direct relationship between physical tool use and design success. The particular focus of interest is in how design tools manifest in real group design settings over the phases of design and associate with the team design success. As summarized in Fig. 1, the scope of this paper is on how the physical context influence cognitive and social processes and design outcomes. Prior research has established relationships between physical context and cognitive processes [2,3] and between cognitive processes and design outcomes [2,4]. Thus, by inference, physical context should also influence design outcomes. But relatively a few studies examined this direct connection [5–8], providing a limited understanding of how the physical context influences designers in the context of larger scale and longer term designs tasks enacted by teams (rather than relatively brief design tasks enacted quickly by individuals) and with broader range of tool use in consideration.

We begin by describing what is known about the two intermediate paths (i.e., from physical context to cognitive processes and from cognitive processes to design outcomes) and then discuss what needs to be considered when examining the overarching effect from physical context to design outcomes.

1.1 Physical Context to Cognitive Processes and Cognitive Processes to Design Outcomes.

Creative problem solving domains (e.g., science, design, and art) including engineering design can be considered as an ill-structured problem [9]. Typically, there is only one certain but abstract goal state for design problems: produce *something* that embodies required functions. The *something* must be designed so as to be capable of performing those functions, but how to obtain the final design and what the end product should look like are largely left in designers' hands. Although clients could demand a specific design for certain part of a product, many other constraints are left uncertain. Freedom and uncertainty, however, are like two sides of a coin; they may support divergent thinking as a consequence of the freedom but hinder convergent thinking as a consequence of uncertainty. In order to reduce uncertainty without losing innovation, it is important to explore and define the right amount of constraints for a design task at hand. From this perspective, design is a process of constraints-creation to reduce uncertainties through iterations of experimentations and refinements, choosing tools strategically. Thus, tools presumably play important roles in shaping constraints by providing various approximate outcomes for uncertainties in design [1,10].

Among available tools, sketches and physical prototypes have had the most research attention [2,3,11–14]. Construing designers as an information processing system, Ullman and colleagues [14]

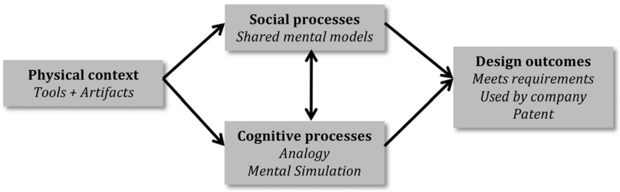

Fig. 1 Schematic pathways of design tool use and outcomes

Contributed by the Design Automation Committee of ASME for publication in the JOURNAL OF MECHANICAL DESIGN. Manuscript received July 8, 2010; final manuscript received December 22, 2011; published online March 6, 2012. Assoc. Editor: Janis Terpenny.

claimed that external representations such as notes, sketches, and computer databases act as extensions to the human memory and they are essential to support smooth information transformation/communication between short-term and long-term memory. Additionally, sketches are "the only reasonable memory extender for mechanical designers," because textual information is not capable of fully characterizing form [14]. Although they did not explicitly discuss any role of prototypes, it is certainly a plausible inference that prototypes would also be a type of extended memory system, only more concrete and tangible than sketches. Consistent with this cognitive modeling endeavor, a survey study of engineering designers found a very high prevalence use of sketches and prototypes during design; 96% of engineers worked with sketches and prototypes to develop solution concepts [13].

In depth, studies on how sketches and prototypes affect designer's cognitive processes were conducted [2,3,10,15]. Particularly, they focused on the differential role of sketches and prototypes in supporting analogy and mental simulation; how tools enable generating distant analogies (which has been associated with innovation) and producing approximation outcomes (more certain answers within boundaries, critical for evaluating design quality). Analogy and mental simulation have been the focus of cognitive processes in design because both have been acknowledged general human capacities, especially underlying creative tasks [16–20]. In addition, both analogy and mental simulation have been found in expert designers and inventors [21–23], and both have been found to be associated with innovation [11,24,25].

The exact role of analogies in design success can be complex. The presence of specific examples has been found to negatively affect originality in design. The proportion of using distant analogies (between-domain rather than within-domain) was a good predictor of product originality [11], and when designers were provided with concrete examples, it was more likely that the resulting products resemble the given examples, limiting the proportion of distant analogies [24,25]. Although within-domain analogy helps creating constraints and reducing uncertainty by providing concrete examples to which designers can refer, it limits broad search for alternatives resulting in narrowed design space.

While distant analogies can contribute to innovation by enabling broad search, mental simulation can do so by offering approximate answers in situations of uncertainty [17,26]. Several verbal protocol studies found that scientists used mental simulations to account for informational uncertainty in data. Astronomers and physicists were observed to frequently use mental simulations as a device to compare hypothesized versus actual results and get estimations of the fit [27,28]. By evaluating the resulting state with the actual data, scientists can identify plausible—being worthy of further study—hypotheses and remove defective explanations. Both of analogy and mental simulation were found to be essential for problem solvers to learn and create new constraints, thereby, resolving uncertainty [10].

If those cognitive processes are core to design, then how do tools affect analogy and mental simulation? Christensen and Schunn [2,3] found that each tool may both support and hinder cognitive processes. They found that eliciting more distant analogies is a key benefit of sketches, but requiring fewer mental simulations was assumed to be a benefit of physical prototypes. In particular, Christensen and Schunn [3] found that occurrence of physical prototypes were associated with fewer technical/functional simulations and more approximation than were sketches, which implies that 3D external representational systems may enable designers to use alternative strategies to acquire approximate answer that cannot be gained from other form of representational systems, thereby inherently reducing uncertainty. This reduced need of mental simulation may bring efficiency advantages for designers' time and effort.

1.2 Physical Contexts to Design Outcomes. The goal of this paper is twofold. As discussed above, one goal is to directly test the assumed direct path from physical contexts to design outcomes. The other goal is to include a broader range of design tools, beyond sketches and physical prototypes, into the framework, such as smart board/drawing boards or CAD software. Most research in the field has focused on the role of sketches and/or physical prototypes in achieving a short-term artificial design task [6,8] or a school assignment [29]. Because each study differed in which tools were provided, how they were grouped, the design task given, and larger design environment provided to the designers, it is difficult to make comparisons across the studies to infer relative effectiveness of each tool in relation to other tools. It is also noteworthy that tools and artifacts other than sketches and prototypes have never gained much attention in spite of their availability and common occurrence in design. Various other tools (e.g., smart boards or CAD program) can support design in qualitatively different ways than do paper sketches or physical prototypes. And as with prototypes and sketches, the relative advantages and disadvantages might apply specifically to convergent or divergent thinking phases, which make each tool especially appropriate for different particular design phases. In addition to the timing of tool use, analyses at the subsystem level also enable comparisons of tool effectiveness at a sufficiently nuanced level because designers must successfully develop solutions for multiple subsystems to solve real design tasks, and tools much support search across those subsystems. By examining the nature of idea search (e.g., breadth, quantity, and elaboration level) undertaken for each subsystem and how this subsystem-level idea search correlates with tool use, we will be better position to further unpack the black box between tool use and design outcome. Further, to improve the effectiveness of use of various tools, comparison across design phases (convergent and divergent thinking) is necessary; some tools may support rich ideation but hinder effective idea evaluation; other tools may have the reverse effect.

1.2.1 Cognitive Processes. Along one of these dimensions, Schrage [30] reviewed the effect of prototype across design phases, with particular interest in the prototyping culture found in industry. He argued that the prototyping culture has a substantial impact on success because early use of prototypes allows for flexible alterations that lead to product innovation within shorter amounts of time. He also found that specification-driven prototypes (i.e., spend a lot of time upfront to develop very detailed specification and then produce a prototype) was dominant before but now corporate culture has moved to prototype-driven specifications, which are realized in rapid and iterative prototyping. In addition, the order of use of prototypes relative to other tool use has been found to be important as well. Whitney [31] found that innovative Japanese car companies design the car body with CAD tools first and then create a clay model as an output of the CAD system, even though perfection was not yet achieved in each detailed part. When designers want to implement changes, another cycle of prototyping only takes 40 days.

While rapid prototyping has become more popular, there are potential drawbacks. As mentioned earlier, concrete examples can hinder the production of distant analogies. In other words, designer may fixate on the current state of a physical prototype and diminish opportunities to consider alternatives. It is often observed that object examples make designers generate products similar to the examples and it is difficult for designers to escape from the given forms [24]. As a related phenomenon to fixation, premature commitment can also arise from prototypes. Premature commitment—a construct that originated in social psychology—occurs when a person uncritically accepts provided information as true, often because the information had little meaning at the time it was first introduced and thus was not evaluated at that time. Later when the uncritically accepted information becomes relevant, one may reach incorrect conclusions due to the "initial mindless acceptance of the information" [32]. In other words, the mode of processing the initial information (e.g., whether taking it for granted or not) affects subsequent use of the information. Applying this notion to design tasks, designers may prematurely commit to an embryonic prototype and take most of the design as they are without giving critical examination to each of parts before having had a chance to consider alternatives, which harms later innovation. Under the influence of premature commitment, even with iterative prototyping, only a small number of minor changes may be done, settling quickly on the premature design.

Although concrete prototypes bring a danger of fixation, physical prototypes promote easy and fast approximations by providing an embodied design for functional evaluations. For example, when a cockpit designer wants to know whether two buttons are placed close enough to be operated with one hand, a prototype can quickly provide a fairly precise answer. Because 3D prototypes can bring the complete design ideas into one physical place as a manipulable object, many uncertainties in design can be avoided.

1.2.2 Social Processes. In addition to tools influencing cognitive processes, tool use may also influence social processes. Design tasks are usually team efforts and collaboration across engineering disciplines is typical. As a result, environments that support collaboration are important for success [33]. In terms of shaping collaborative workspace, the "spatiality of human interaction" is an important consideration [34–36]. This idea has been much studied in remote workspace settings, and in a review, Olson and Olson [34] argued that collocated workspaces should not be replaced with remote workspaces even with the development of increasingly sophisticated distant communication technologies. Because many aspects of synchronous interactions are best supported by collocation (e.g., rapid feedback, multiple communication channels, shared local context, implicit cues, and spatiality of reference), whether team members and tools are collocated in a space or not (i.e., whether information can be readily shared or not) is important.

Particularly when people work on tasks that are associated with high ambiguity and when team members' work is strongly dependent upon each other (e.g., design), it is very difficult to do the work in disparate spaces [34]. Whittaker and Schwarz [36] observed that software developers chose to work with a large paper wallboard in a public space, rather than with electronic group tools, to discuss problems in design and to be informed of each others' progress. Likewise, whether a tool is sharable or not is essential for promoting group interaction. Less-sharable tools such as an individual's computer, laptop, and paper notes support the individual's work. Individuals can work well in parallel within their own design spaces when they have a shared understanding of what each member has to do. But more-sharable tools such as smart boards and physical prototypes support collaborative work by enabling construction of shared mental models. A large sharable screen such as a smart board provides enough space for a small group of people to discuss while writing and drawing ideas. The aggregated ideas on the board can be stored and retrieved; thus, the board can serve an extended memory system for a team to store shared mental models. Also, a physical prototype affords a shared mental model by realizing ideas about different aspects of the design into an integrated object. Especially when a team consists of designers from various disciplines, prototypes can play a large role in bridging disciplinary and functional boundaries [30]. By physically showing how ideas from a designer's own discipline are implemented and by observing how ideas from the other designers' disciplines are implemented, a more accurate and shared understanding becomes possible.

In sum, we predict that relative to unsuccessful teams, successful design teams will use more collaborative work supporting tools (i.e., smart board and prototype) rather than individual tools (i.e., computers, laptops, and notes) and the differences in tool use will vary by the timing of use. Tool use is expected to support idea search differently at the level of subsystem ideation. To examine the relationships between design tools and success as predicted by prior work on tool effects on designers' cognitive and social processes, we collected naturalistic data from engineering students designing real products.

2 Methods

This study takes advantage of a broad data collection effort involving a number of aggregate as well as fine-grained data sources (i.e., expert evaluations, background surveys, video recordings, project presentations, and project reports) from an atypically large number of student engineering teams working over multiple months on a project.

2.1 Participants. To collect a sufficient number of teams to support statistical comparisons of successful and unsuccessful teams, data were collected across eight consecutive semesters (Fall, Spring, Summer). Students were offered $200 and the use of high quality meeting space for participation in the study; all but a small number of teams who were unable to meet regularly on campus volunteered for participation. In total, the dataset consisted of 53 multidisciplinary engineering teams (each consisting of groups of three, four, or five students) who were enrolled in a full-semester product realization course (44 teams were from sections of a general product realization, nine teams from a special section focused on product realization for global opportunities, but taught by the same instructors and at the same time as the general course in two semesters). Given the advanced background knowledge and experience this course required, only more advanced undergraduate or graduate students who have completed primary undergraduate degree requirements could enroll for the course. Students were primarily juniors and seniors, with a few masters' students, who were majoring in Bio, Industrial, Chemical, Mechanical, and Electrical/Computer engineering programs. Analyses were restricted to the 43 teams that worked on hardware-focused projects (i.e., projects that focused on the design of mechanical/electrical objects, excluding software or process design projects; 34 teams from product realization and nine from product realization for global opportunities). This selection was done to generally make the overall design tasks more equivalent across teams and specifically to equate for the end-state need to create a physical prototype given our goal to examine the relationship between tool use and success.

2.2 Physical Design Tools and Artifacts. In this naturalistic study, the physical design context consisted of computers, notes, smart boards (electronic whiteboards), and physical prototypes. Computers (including laptops) are the most common tool that engineering designers use, and they enable 2D and 3D drawings along with basic functions such as documentation and data management. Note taking (on blank paper or printed out documents) is a handy and effective tool that designers often choose to record plans and sketch ideas. Whiteboards are commonly found in many workplaces including design facilities. As a high-end form of a whiteboard, the observed rooms were equipped with smart boards. Functions available in computers and white boards are combined in smart boards, affording a large screen with easy data storing and retrieving. In addition, using a smart board prevented a single team from taking over the wall space in the shared room. Prototypes can be defined in several different ways; for example, by their purpose [37] or by their developmental stages [38]. In this study, we defined physical prototypes as any tangible 3D artifacts that designers bring into the design process regardless of their purpose or developmental stages, which included related designs created by others, raw material to be integrated into a design, physical pieces from the environment to which the design must be integrated, early models of the final design, and the final model developed by the team. Sketches on paper or designs on the computer are excluded even though they are sometimes taken as a functional prototype—in this study, we did not have the visual resolution to be able to determine the details of what was on paper, laptop screens. Further, as noted in the literature review, physical

3D objects may have a different effect on designers than 2D objects, and thus we wanted to code them separately. Finally, everyday objects that just happened to be in the environment, such as the table, soda cans, pens, cell phones, or key chains (i.e., not an artifact created by a designer for the design task at hand) are excluded, even though such objects can sometimes act as an analogical example during a design conversation [8]—such objects are in the design environment 100% of the time, and it is not possible to effectively code from video when they are visually encoded or not encoded by the design team.

2.3 Course Description. There were two variations of a core course. The basic *product realization* course had projects of various goals and constraints assigned to student with individuals or industrial companies as their clients. Students worked on projects with a range of requirements and often met with clients as they progressed to narrow down their design space and produce specific prototypes. By contrast, the *product realization for global opportunities* course (offered less often and always with shared instructors and lectures to the product realization course) provided projects sharing an additional common constraint, i.e., designing sustainable products for use in developing countries in mind and all teams collaborating with engineering faculty from a particular university based in Brazil. In terms of the curriculum, this course covered all of the techniques and objectives of the *product realization* course but with an international component and perspective added. Students took a trip to Brazil during spring break (approximately the middle of the semester) in order to observe the needs context first hand and to collaborate in person with the Brazilian faculty mentor.

Although the two courses differed in a few details, both courses entailed common essential features: an engineering design course that pursues hands-on experience with real product design problems possibly aiming at patentable innovation and business plans for implementation. Both shared the same overall milestones/major design activities, which were (1) defining user requirements, (2) concept generation and selection, (3) creating computer based design and analysis models, (4) benchmarking early designs with existing products, (5) rapid prototyping and reverse engineering techniques, and (6) developing a functional prototype. As learning outcomes, both courses were offered to build success in a broad range of skills related to innovative engineering design: developing abilities to design a system, component, or process to meet the desired needs within realistic constraints; to function in multidisciplinary teams; to identify, formulate, and solve engineering problems; and to communicate effectively. Therefore, teams in both courses were equivalent in that they were real design teams with some previous experiences working on real world problems.

Also, the shared and consistent overall framework of the courses ensured reasonable comparison across terms and courses. Both courses used a similar time schedule, assignments, and professional and monetary supports. At an abstract level used in our analyses to separate the different temporal effects of design tools, the course schedules consisted of two phases: an ideation phase (relatively more divergent search) and a refinement phase (relatively more convergent search), each spanning approximately 8 weeks. During the ideation phase, teams analyzed their design problem by, among other activities, identifying and refining client requirements along with possible technical constraints, and generating and selecting concepts. Based on their analyses, each team made a design plan and presented it in class to receive feedback from peers and instructors (midterm presentation). After plans were adjusted, the refinement phase began. Teams focused on a small number of possible design candidates and then created, assembled, tested, and refined prototypes. Following the period of experimenting, teams built upon the best design generated thus far, now taking design-for-manufacturing and cost analysis into account. The course finished with a final poster and design symposium presentation. A final written report was submitted 1 week after the final presentation.

Across the courses and terms, the same basic assignments were given to students. Each team gave two major presentations—midterm and final presentations—along with biweekly update presentations and submitted one final report at the end. In terms of professional support, students in both courses were assigned an academic and industrial advisor to meet with at least once per week, with encouragement to meet several times per week. There were weekly mandatory classes in which the instructor gave lectures covering important topics that are directly related to the course. Several other engineering faculty and staff with expertise in new product development were also available for consultation during the semester. To complete the development of their product, each team was given a budget, up to $2500, that could be used to purchase raw materials, purchase product components (i.e., motors, computer chips, cameras), create prototype parts, print reports and posters, and any other miscellaneous items that are required to develop the new product.

2.4 Background Survey. During the first week of the course, a survey was distributed to collect data on students' prior experiences with engineering design. Background survey data were only collected from 72% of teams due to lack of compliance by some teams and oversight in survey administration during two semesters. The survey consisted of seven multiple-choice questions asking about the breadth and depth of their design experience, CAD skills, and knowledge. The questions covered the number of years of experience working as a full-time engineer, the number of design projects they experienced in college courses (university-level design) and at an internship (industry design), their proficiency in CAD software and other design analysis tools (e.g., Finite Element software, House of Quality, Classification trees and tables), and the presence of precollege design experience. Questions could be grouped for three subdimensions: university-level design experience (three items), outside university experience (2), and tool proficiency (2). Based on the general finding that skill increases at less than a linear rate as a function of amount of experience [29], the answer choices were spaced qualitatively, rather than spaced absolutely by a numerical scale. For example, a question asked what prior experience a student had with Solidworks or other 3-D CAD software and the choices were (a) none, (b) one class, (c) several classes, (d) internship experience/work experience, (e) one class and internship/work experience, and (f) several classes and internship/work experience. The number of answer choices varied by content of each question and the possible maximum total score of the background survey was 21.

2.5 Design Tool Use Observation: Video Recording. Upon obtaining consent to participate in the study, students were asked to conduct all the design work for the product realization class as they normally would but do the design activities in the two provided lab spaces. Both lab spaces were equipped with wall-mounted video and audio recording devices that recorded all activity in the room automatically. Each lab space was also equipped with a meeting table with four chairs, a SMART^{TM} board (42-in. LCD display with a touch screen overlay) mounted on a wall (and its own computer for running the electronic whiteboard software), and a desktop computer (with 17-in. monitor and inkjet printer) equipped with all the design software that the teams would need. Each team had their own login account for the desktop and smart boards such that there was no conflict between teams for long-term storage of information. There were four video cameras covering: (1) from-the-side view of the whole room; (2) table top-down view; (3) over-the-shoulder view of the smart board; and (4) screen capture from the desktop computer. Each view recorded automatically when a pixel change was detected.

This paper focuses on examining the over 1000 h of whole room view video to observe the overall usage pattern of various design tools (i.e., computer, smart board, notes, prototype). Given the volume of data and resolution of video data, we examined the relative amount of tool use (see coding section for details) rather than examining in depth the contents of use of each tool separately.

2.6 Design Products as Indices of Success. Measuring design success is a complex process with a variety of possible solutions. In this context, each team is working on their own design task, so it is important to come up with a common metric that fairly assesses the team's progress on the task rather than measuring the difficulty of the task they were assigned or the difficulty of the task the team chose to attack. In creativity settings, one technique is to use holistic ratings made by a panel of experts [39]. The range of projects being designed and the lack of detailed contextual information (e.g., detailed knowledge of each client's requirements, or what technologies were readily available at the time each team was conducting their design process) made it impossible to find a panel of experts with sufficient knowledge to make high validity assessments.

Instead, the approach we used applies a content-focused rubric aligned to the details of each design project and builds upon the expertise and project-specific knowledge of the instructor. At the beginning of each semester, the instructor was interviewed about each project to specify appropriate levels for a complete set of requirements for each project based on knowledge of the client and technological constraints. The rubric consisted of detailed, objective (and weighted) dimensions involving cost, functional performance, human factors, reliability, product life cycle concerns, and manufacturing requirements and included minimal and ideal levels. For example, one team had to design a wireless power-consumption measurement device with an ideal cost of less than $100 and a minimal cost of $100. At the end of each semester, the instructor was interviewed again to determine, for each requirement, whether the previously listed requirement level was exceeded (4), just met but not exceed (3), fell just below the requirement (2), or fell greatly below the requirement (1). Defining the requirements early in the semester and in very concrete object terms ensured that the success score primarily reflected the success of the outcome rather than the process and there was little room to be subjective. An average score across all the requirements was computed to determine overall team success levels. As an external validation of the success score, the scores were significantly correlated with sponsors' evaluation of willingness to use the design at their companies, $r = 0.45$, $p < 0.02$. Note we did not use sponsor use estimates as the focal measure of team success because of possible unevenness in reporting across so many sponsors and the likely effects of political factors beyond the team's control that influence company decisions.

As a secondary success measure, the success score for the subsystems (i.e., energy source, material, data transmission, logic control) that were commonly found across the projects (21 out of 43) was available. In order to measure design idea search within each subsystem, teams' slides presented along the course were used as a primary data source. These slides contained the core ideas that each team explored, as validated by examination of student journals from a subset of the teams. As part of another analysis effort with this dataset, it was found that only the number of elaborated ideas—the number of alternatives considered and described in at least partially detailed manner (i.e., more than just mentioning the idea), not simple quantity or breadth of idea search, predict the subsystem success [40].[1] Therefore, our in-depth analysis will involve how design tools support an increasing number of elaborated ideas, which is an index of team creative fluency, at the subsystem level.

3 Results and Discussion

3.1 Data Coding

3.1.1 Background Survey. The seven multiple-choice questions were coded numerically using the following coding scheme: responses indicating no experience on each question (e.g., no prior experience with CAD software, zero month of employment as a full-time engineer, or zero semester of internship) were coded as zero. Other responses indicating presence of experience or longer/more experience were coded incrementally with one-unit increases. For example, the question asking about prior experience with CAD software was coded as: none as 0, one class as 1, several classes as 2, internship experience/work experience as 3, one class and internship/work experience as 4, several classes and internship/work experience as 5.

Two aggregate team experience measures were produced from the experience data: team average experience score and team max experience score, with the idea that the most experienced team member could serve as a leader for parts of the overall design task. Team average experience score is the mean of each team member's experience score in percent. Team max was computed by extracting the highest score among the team members for each question (also in percent).

3.1.2 Design Tool Use Observation: Video Recording. Videos for all 1247 h were coded by hand using a log sheet. Each video log included date, room number (there were two rooms in parallel use every semester), and tool use. In order to code the tool use systematically, common keywords of each available tool were provided to the coders. The categories were (1) *computers* including laptops, (2) *smart board*, (3) *notes* including blank paper and printed out documents, and (4) physical *prototypes*. The keyword *computers* could be used for cases in which a team is using the computer equipped in the lab and/or individual laptop(s). Similarly, *notes* included reading/taking notes and/or using any other form of papers (e.g., printed documents). Each category was coded separately because the categories were not mutually exclusive; multiple tools could have been used at the same time (e.g., paper with computer, or prototype with paper). Due to the large volume of data (~10,000 entries of different tool use) and the simple coding scheme (i.e., 1 or 0 binary coding for the use of each tool at a moment), coding was divided and done by several undergraduate research assistants. Coders were blind to the purposes of the study and each team's degree of success. A subset of data (~10%) was coded again by additional coders to check the reliability, and average reliability across the tools was found to be very high, kappa = 0.98.

The log included team number, start time, end time, number of people in the room, tools used (in keywords), and comments. The start time and end time were contingent upon a change in tool use. For example, if two members of a team started using the smartboard for 5 min from 14:22 to 14:27 and then a third member entered with a laptop, the first row of the table would have a record of the start time as 14:22, the end time as 14:27, the number of people as 2, the tool used as *smart board*, and the last column with brief comments on the situation. The second row would have 14:27 as the start time, 3 as the number of people, and *smart board* and *computer* as the tools used. A new row was used each time the situation changed. In sum, the coding of team tool use was segmented based on the tool use.

3.2 Analyses

3.2.1 Grouping Teams by Success. To examine the relationship between tool use and failure (i.e., high + medium versus low)

---

[1] For a given subsystem (e.g., energy source), all ideas mentioned across team documents were collected. The full set of subsystem ideas were then sorted according to similarity by multiple experts to produce idea tress for each subsystem in which more similar ideas were more closely connected in the tree. Number of ideas explored by a given team was the number of leaf nodes examined. Breadth of ideas searched was the number of different branches explored at given height in the tree; several different levels were considered but produced similar outcomes. Each idea was also coded for four different levels of elaboration—just mentioning the idea, providing a more detailed verbal description of the idea, providing a more detailed verbal description of the idea, drawings (sketches or computer) illustrating possible instantiations of the idea, or drawings illustrating ideas functioning the design.

or innovative versus incremental success (i.e., high versus medium) of the design teams, first, the teams were divided into high (average rating above 3 out of 4, indicating outcomes well beyond minimal expectations), medium (average rating between 3 and 2, indicating outcomes just above minimal expectations), and low (average rating less than 2, indicating outcomes below minimal expectations) success groups. Using these success definitions, the 43 teams fell into 21 high, 17 medium, and five low success teams.

For the time-on-task analyses, two measures of team meeting time were examined: total meeting time and total people time. The total meeting time represents the total hours a team has met during the term, regardless of how many people were present at any moment in time. The total people time indicates the collective team hours taking into account the number of team members involved at each segment.

Although there was a large range of time that each time spent working on their projects, there was no statistically significant difference in the group mean time across the three success levels either in the total meeting time (see Fig. 2) or in the total people time (High: $M = 68$ h, $SD = 39$ h, Medium: $M = 72$ h, $SD = 34$ h, Low: $M = 92$ h, $SD = 72$ h). Thus, given the similar mean amount of time invested to design a product, overall differences in success across the different groups are presumably attributable to how they utilized the time, although we acknowledge that there may have been differences in time spent alone, outside of the provided design space, across the success levels. The lack of a total meeting time difference also removes the worry of having to differentiate between percent tool use and raw amount of time using tools.

Another major concern for our core correlational analysis is that the high success teams might have had students with more prior knowledge and experience than did the other teams as well as different tool preferences, and so differential tool use by team success levels might merely be an indirect association mediated through designer expertise. However, there was no statistically significant difference across the three success groups in terms of prior design experience. As shown in Table 1, neither the team average experience score, $F(2, 28) = 1.280$, MSE (Mean Squared Error) $= 0.012$, $p = 0.29$, nor the team max experience score differed by the level of success, $F(2, 28) = 0.298$, MSE $= 0.006$, $p = 0.74$. Most importantly, the highest success group did not even have the highest average or max experience levels, and the lowest success group actually had the highest max experience level.

3.2.2 Tool Use by Success: How Design Tools Use Correlates With Team Success. If collaborative and sharable tools (i.e., smart board and prototype) support successful design outcomes, successful teams (21 high and 17 medium success groups) should show more use of such design tools than unsuccessful teams (five low success group), which forms the failure contrast, high + medium versus low. Alternatively, tool use differences may only be seen between medium and high groups, which forms the incremental versus innovative success contrast, high versus medium. These two contrasts form a priori orthogonal contrasts. That is, these statistical contrasts were created at the start of the project on theoretical grounds rather than from exploration with the data, and they are mathematically orthogonal. The vector contrasts (i.e., [0.5, 0.5, −1] and [1, −1, 0]) have a dot product of zero; a priori orthogonal contrasts do not require post hoc statistical corrections [41].

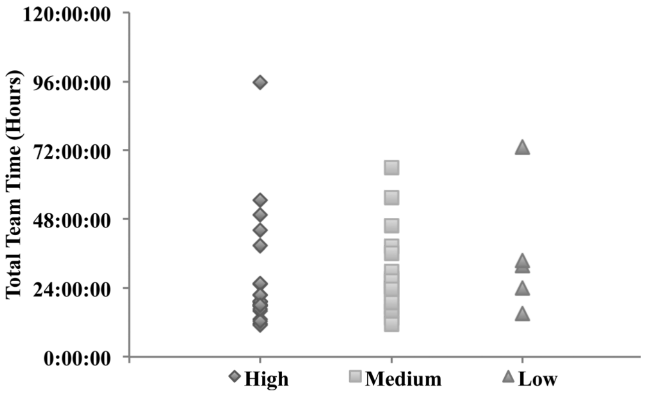

Fig. 2 Hours of total team meeting time by team success levels

Table 1 Group means and standard deviations for team average and team max experience (both in %) by success group

	Team average experience		Team max experience	
	M	SD	M	SD
High ($N = 14$)	35	10	66	13
Medium ($N = 14$)	38	10	67	16
Low ($N = 3$)	29	8	73	14

Tool use time—percentage of time each tool was used out of total team time—was then analyzed for each design tool by the three group success levels. As shown in Fig. 3, high and medium success groups did not differ statistically; the main statistical differences between groups were between low success groups and the other two groups. More specifically, compared to the low success group, high and medium groups used sharable tools (i.e., smart board and physical prototypes) more often. The high and medium group teams used smart board 15% more often ($M = 25$, $SD = 22$) than did the low group teams ($M = 10$, $SD = 7$), $t(19) = 3.25$, $p < 0.01$, Cohen's $d = 1.1$. Considering that the average meeting time of all groups was approximately 30 h, successful teams used the smart board 4.5 h more often than did unsuccessful teams. Prototypes was also used more statistically often by the high and medium group teams ($M = 13$, $SD = 15$) than by the low group teams ($M = 5$, $SD = 5$), $t(16) = 2.32$, $p = 0.03$, Cohen's $d = 0.8$. No statistically significantly different pattern of tool use was observed for computers, $t(41) < -1$, $p = 0.57$, or notes $t(8) = -2.02$, $p = 0.08$.

It appears that successful teams used tools that support collaborative work (smart board and physical prototypes) more often than did unsuccessful teams. This tool use pattern presumably suggests

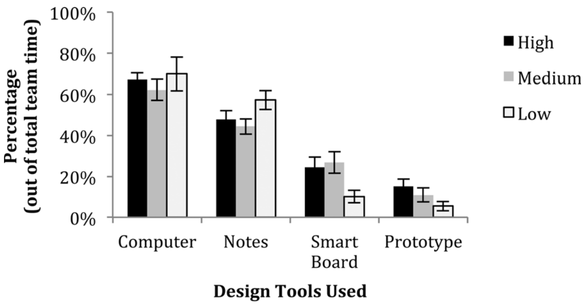

Fig. 3 Percentage of each design tool use by the function of success group. Note that multiple tools could be used simultaneously, and thus the sum of the tools percentages typically exceeds 100%.

Table 2 Intercorrelations between design tools

	Nonsharable tools		Sharable tools	
$N = 31$	Computer	Notes	Smart board	Prototype
Computer	—	0.11	−0.45*	0.10
Notes		—	−0.21	−0.10
Smart board			—	−0.24
Prototype				—

*$p < 0.05$.
**$p < 0.01$.

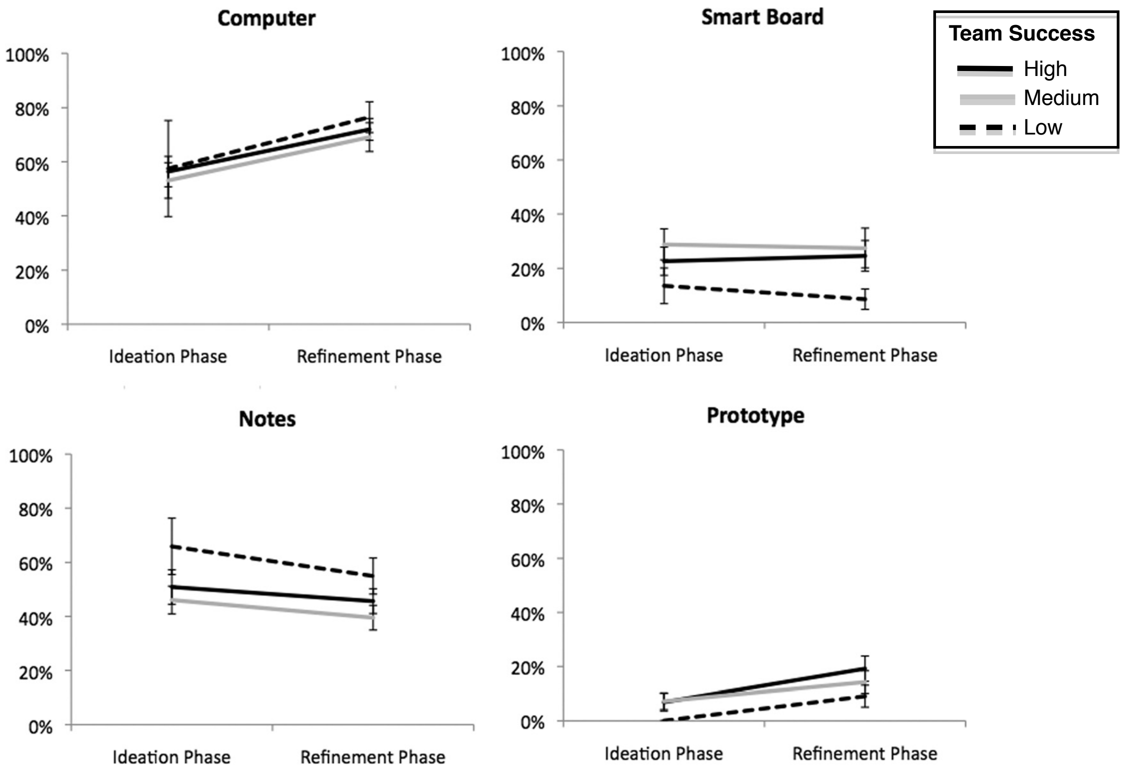

Fig. 4 Percentage of each design tool use by the function of success group and phase

longer hours of group discussion supported by the large sharable screen of the smart board and tangible prototypes.

To address the question of whether the tools are in opposition or follow similar patterns (i.e., whether associations with success might be mediated), intertool correlations were examined (Table 2). Use of smart board was negatively correlated with the use of computer. This negative correlation can be considered as evidence that the categorization between sharable tools and nonsharable tools is valid; the smart board supports collaborative work and the computer supports individual work, and the two tools are rarely used simultaneously. In addition, the nonsignificant negative relationship between smart board and prototype suggests that the effects of the smart board and physical prototypes on success are separate effects: the use of a sharable large screen *and* the use of concrete prototypes contribute to successful designs.

3.2.3 Tool Use by Phase and Success: How Tool Use Changes Over Time Within Each Success Group. To examine how design tools supported projects differently as the projects progress, tool use time was analyzed as the function of the two most salient project phases (i.e., ideation versus refinement phase) and the failure contrast found to be the locus of tool use differences (high and medium versus low success). A conventional overall 2×2 MANOVA was not used because the assumption of homoscedasticity was not met;[2] instead separate t-tests were used by phase across groups and by groups within phase and corrected *df*s are reported whenever needed with t-tests assuming unequal variance.

First, paired sample t-tests were conducted by the function of phases (collapsing by success groups). As shown in Fig. 4, computer was used more often by all groups in the refinement phase ($M = 55$, $SD = 27$) than in the ideation phase ($M = 71$, $SD = 19$), $t(42) = -3.82$, $p < 0.001$, Cohen's $d = 0.7$, which presumably reflect increased use of design software to finalize the details of a design once after the final design was selected. Similarly, physical prototypes were used more often by all groups in the refinement phase ($M = 6$, $SD = 13$) than in the ideation phase ($M = 16$, $SD = 19$), $t(42) = -3.58$, $p = 0.001$, Cohen's $d = 0.6$. By contrast, the smart board and notes were used at stable levels throughout the semester. Specifically, a smart board was used in the ideation phase ($M = 24$, $SD = 23$) as often as in the refinement phase ($M = 24$, $SD = 27$), $t(42) = 0.04$, $p = 0.97$. Although the use of notes showed a slight decrease in the refinement phase ($M = 44$, $SD = 20$) compared to the ideation phase ($M = 51$, $SD = 26$), the difference was not statistically significant $t(42) = 1.61$, $p = 0.12$.

Second, for each phase and tool, t-tests were conducted on the failure contrast (high and medium versus low). As shown in Fig. 4, there were no statistically significant differences between success groups in either phase in terms of use of computer and notes; computer (ideation phase: $t(41) = -0.19$, $p = 0.85$, refinement phase: $t(41) = -0.63$, $p = 0.53$); notes (ideation phase: $t(41) = -1.41$, $p = 0.17$, refinement phase: $t(41) = -1.3$, $p = 0.2$). In the use of smart board, however, there was a significant difference specifically in the refinement phase. The difference in smart board use between high/medium group teams ($M = 25$, $SD = 24$) and the low group teams ($M = 14$, $SD = 15$) was not statistically significant in the ideation phase, $t(41) = 1.1$, $p = 0.28$, but the difference was larger and statistically significant in the refinement phase $t(19) = 2.9$, $p < 0.01$, Cohen's $d = 0.96$. Said another way, successful group teams used the smart board consistently throughout the term ($M = 26$, $SD = 28$) but the low success group teams reduced smart board use in the refinement phase ($M = 9$, $SD = 8$). This pattern may suggest that low success teams focused more on working individually rather than working as a group after they selected their final design and divided up the work across the team members.

Also, in terms of use of prototypes, teams showed different tendencies over time by level of success. The difference between high/medium and low success teams in use of prototypes was not statistically significant in the refinement phase (high and medium: $M = 17$, $SD = 20$; low: $M = 9$, $SD = 9$), but successful group teams used prototypes significantly more often ($M = 7$, $SD = 14$) in the ideation phase than did unsuccessful group teams ($M = 0$,

---

[2] Box's test for equality of covariance matrices: $F(20, 422) = 1.59$, $p = 0.05$; Levene's test for equality of error variances: Computer, $F(3, 82) = 3.00$, $p = 0.035$, Board, $F(3, 82) = 2.10$, $p = 0.107$, Notes, $F(3, 82) = 1.46$, $p = 0.233$, Prototype, $F(3, 82) = 3.99$, $p = 0.011$. Normality assumptions were met.

$SD = 0$), $t(37) = 3.16$, $p < 0.01$. The observation that unsuccessful teams never used prototypes in the ideation phase may imply that the benefits of embodied design outweigh the problems of premature commitment; even with a danger of premature commitment, which may hinder teams from producing highly innovative design, it might be worse for design teams to reason with prototypes only very late in development. While it is theoretically possible that successful teams created their final prototypes earlier in the semester, in general the physical prototypes found during the ideation phase were more commonly alternative related designs found in the market, early unsuccessful designs, or related objects from the design environment. Thus, we do not believe the ideation phase difference by success levels is a circular result of early success (as measured by outcomes) reflecting success (as measured by products), but this relationship cannot be entirely ruled out.

How did tool use relate to the space of ideas considered? In particular, did tool use correlate with the number of ideas elaborated beyond a minimal level, the best idea search metric associated with team success? Tool use in the refinement phase was regressed against the amount of elaborated subsystem ideas. The multiple regression analysis showed that three tools—notes ($ß = 0.54$, $t(16) = 4.31$, $p = 0.001$), smart board ($ß = 0.47$, $t(16) = 3.77$, $p = 0.002$), and prototype ($ß = 0.53$, $t(16) = 4.42$, $p < 0.001$)—but not computer ($ß = 0.06$, $t(16) = 0.48$, $p = 0.64$) were significantly (and independently) associated with number of elaborated ideas, $R^2 = 0.73$, $F(4,16) = 14.46$, $p < 0.001$. Consistent with previous analyses, smart board and prototype appeared to promote success at the level of subsystem as well as at the global level, by supporting elaborated ideation. Presumably, the increase in ideation may be attributable to the concreteness of physical prototype and sharability of smart board, which would elicit in-depth and team-wide discussion on refinement and evaluation of the near-end product. Interestingly, notes, which appeared to generally hinder successful design in above analyses, also contributed positively to idea elaboration. This surprising result could in part be due to diverse types of notes; follow-up studies should take a closer look at the contents of the notes (e.g., were they sketches, lists, CAD images, or printouts from the Internet?). Alternatively, thinking about the general function of note taking, notes can also act as a handy extended memory system that can store products of ideation. In other words, the use of notes may reflect increased documentation of ideas rather than increased ideation per se.

3.2.4 Tool Use by Background survey: How Prior Experience Predicts Tool Use. To identify the relationships between experience and design tools management, we examined correlations among the measures. Because many of the scales are not true interval scales, we use Spearman's rho (i.e., a rank-order correlation). As shown in Table 3, the two experience measures are strongly but not perfectly correlated with each other, allowing for some differentiation of whether general experience or local expertise are critical.

If experience produces a habit of effective tool use, especially the use of sharable tools in collaborative work settings, experience should show positive correlations with the degree of use of sharable tools. Consistent with such a relationship, smart board use is positively correlated with the mean team experience level; more experienced teams used smart board more often. The correlations with components of experience (i.e., university-level experience, outside university experience, and tool proficiency) showed that smart board use significantly correlated with team average of outside university experience ($r = 0.45$, $p = 0.01$) and no other significant correlation was identified at this level of analysis. Interestingly, there was no such a relationship with prototype use. Further, max experience did not predict any kind of tool use. It might be the case that outside university design experience has promoted the use of sharable tools in collaborative work setting, because such design projects often involve team efforts whereas many university experiences are individual efforts. That the team's maximum experience score does not correlate with any tool use may suggest that tool use in group settings is an individual-level rather than leader driven choice, or that these teams functioned more as teams of peers than teams with a leader.

Table 3 Intercorrelations between background survey scores and design tools

	Experience scores		Design tools			
$N = 31$	Team average	Team max	Computer	Smart board	Notes	Prototype
Team average	—	0.50**	−0.10	0.37*	−0.27	−0.05
Team max		—	−0.09	−0.00	0.16	0.07

*$p < 0.05$.
**$p < 0.01$.

4 General Discussion

The findings from this study suggest that design tool use may support and hinder design processes depending on what tools are used, with some interactions with design phase. First, successful engineering design teams used tools supporting collaborative work more often throughout the process than did unsuccessful teams. Consistent use of a smart board and physical prototypes likely promote productive group discussion with accurate and flexible updating of shared mental model and to may also provide unique and various ways of acquiring approximations for upcoming technical and functional constraints. Second, the effectiveness of a tool differs somewhat by time. In particular, late adoption of prototyping was an especially clear hallmark of unsuccessful design teams. Extensive use of tools that support individual work was another characteristic of unsuccessful design teams in general; but when notes were used during refinement phase, they were observed to be helpful in generating a greater number of elaborated ideas. Third, teams' average design experience was associated with various tool use, whereas maximum experience did not play a role. Among various types of design experience, only outside university design experience correlated positively with the use of smart board, suggesting that people with industrial work experience in design teams may have learned the importance of group discussion and clear mental model shared among members of an interdisciplinary team. The observation that use of prototype did not correlate with any kind of experience raises educational/training issues, because not only was the use of prototype strongly associated with design success but also because the effect of prototypes on design cognition can be complex in nature and changes dynamically in time.

In the perspective of social processes, greater use of sharable tools in successful teams goes with literature arguing for the importance of shared visual workspace [34,42]. Having a shared workspace facilitates building and updating common ground and situation awareness, which leads to efficient and effective group discussion. Presumably, when teams hold discussions while using a smart board or a physical prototype, they were able to communicate clearly by direct referencing—and easy writing or drawing in case of smart board. It not only puts everyone "on the same page" but also saves time that otherwise might have been spent on additional explanations or unproductive minor conflicts resulting from miscommunication.

In terms of cognitive processes, the use of the smart board and physical prototypes may have supported working memory and flexible/transitional thinking across different presentation modalities, resulting in multifaceted uncertainty resolution. Both sketches and physical prototypes have been argued to provide information in unique and irreplaceable forms of presentation. Diagrams and drawings act as external memory and an aid for shifting focus (e.g., what aspect of design a drawing emphasizes), which not only extends working memory capacity, but also presents a new way of interpreting design problem or proposed solution [43]. In contrast, there are merits that only tangible objects can provide, such as embodying abstract concepts and revealing discrepancies between theoretical models and hardware behavior [8]. Prototypes that appeared in early design phase were more likely to be only a piece of raw material or a small part of the candidate design, that is, something simple and abstract. These early partial prototypes may have been less subject to the risk of premature commitment or fixation and instead allowed the design team to quickly evaluate early ideas and/or observe the need for alternative ideas. In-depth examination of the nature of the conversations when using the smart board and physical prototypes are necessary to delve deeper into the effects of the tools on social and cognitive processes.

The current study used a correlational approach, taking a detailed behavioral look at a large number of design teams working on real design tasks over an extended time. It is important to acknowledge the limitations of correlational approaches: there is inherent ambiguity regarding the causal connection between tool use and design success. However, we have ruled out a number of plausible third-variable explanations, such as time-on-task and prior experience levels. Further, this study goes well beyond typical studies of extended complex design teams by having studied a large number of teams and used more than just self-report surveys, which often provide biased and incomplete measures of designer activities.

To complete a detailed map of the complex relationships between design tools, affected mental processes and successful outcomes, more work remains to be done. Comparing to prototype and sketches, the effects of smart boards and computers on analogy and mental simulation have not gained much attention, despite their prevalence. Moreover, interrelations/interdependence between tools and order effects of tool use are another critical elements to uncover an optimized recipe of tool use.

Also, although the current study strongly suggests that choice of design tool matters, the content of the work to be best done within each tool is left underspecified. Different tools can support the same type of work, and a single tool can support different types of work. For example, a sketch can be drawn on a paper or with a CAD, but the artifact (i.e., a sketch) embodied in each tool provides qualitatively different functionalities. Thus, future efforts should address tool use dynamics in association with the work content of tools and resulting artifacts, based on more fine-grained analyses.

To conclude, although the complex underlying mechanisms regarding how tools support and hinder social and cognitive process of design activity should be explored in greater depth, the current results support a general recommendation to use sharable tools (e.g., a smart board) more often and to reason with 3D artifacts (prototype) earlier in design, especially in the context of team design work. Further, engineering education may benefit from teaching the importance of sharable tools and early physical prototyping as part of design instruction.

Acknowledgment

The research was supported by NSF grant SBE-0738071, SBE-0823628, and SBE-0830210 to the second author.

References

[1] Gero, J., 1990, "Design Prototypes: A Knowledge Representation Schema for Design," AI Mag., **11**(4), p. 26.
[2] Christensen, B., and Schunn, C., 2007, "The Relationship of Analogical Distance to Analogical Function and Preinventive Structure: The Case of Engineering Design," Mem. Cognit., **35**(1), p. 29.
[3] Christensen, B., and Schunn, C., 2009, "The Role and Impact of Mental Simulation in Design," Appl. Cognit. Psychol., **23**(3), pp. 327–344.
[4] Casakin, H., and Goldschmidt, G., 1999, "Expertise and the Use of Visual Analogy: Implications for Design Education," Des. Stud., **20**, pp. 153–175.
[5] Yang, M. C., 2005, "A Study of Prototypes, Design Activity, and Design Outcome," Des. Stud., **26**(6), pp. 649–669.
[6] 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.
[7] Vidal, R., Mulet, E., and GÛmez-Senent, E., 2004, "Effectiveness of the Means of Expression in Creative Problem-Solving in Design Groups," J. Eng. Des., **15**(3), pp. 285–298.
[8] Brereton, M., and McGarry, B., 2000, "An Observational Study of How Objects Support Engineering Design Thinking and Communication: Implications for the Design of Tangible Media," CHI 2000 *Proceedings of the SIGCHI conference on Human factors in computing systems*, ACM, The Hague, The Netherlands, pp. 217–224.
[9] Simon, H. A., 1973, "The Structure of Ill-Structured Problems," Artif. Intell., **4**, pp. 181–201.
[10] Ball, L., and Christensen, B., 2009, "Analogical Reasoning and Mental Simulation in Design: Two Strategies Linked to Uncertainty Resolution," Des. Stud., **30**(2), pp. 169–186.
[11] Dahl, D., and Moreau, P., 2002, "The Influence and Value of Analogical Thinking During New Product Ideation," J. Mark. Res., **39**(1), pp. 47–60.
[12] McGown, A., Green, G., and Rodgers, P. A., 1998, "Visible Ideas: Information Patterns of Conceptual Sketch Activity," Des. Stud., **19**, pp. 431–453.
[13] Romer, A., Pache, M., Weisshahn, G., Lindemann, U., and Hacker, W., 2001, "Effort-Saving Product Representations in Design-Results of a Questionnaire Survey," Des. Stud., **22**, pp. 473–491.
[14] Ullman, D., Wood, S., and Craig, D., 1990, "The Importance of Drawing in the Mechanical Design Process," Comput. Graphics, **14**(2), pp. 263–274.
[15] Ahmed, S., and Christensen, B., 2009, "An In Situ Study of Analogical Reasoning in Novice and Experienced Design Engineers," J. Mech. Des., **131**, p. 111004.
[16] Holyoak, K., and Thagard, P., 1996, *Mental Leaps: Analogy in Creative Thought*, The MIT Press, Massachusetts, USA.
[17] Kahneman, D., and Tversky, A., 1982, "The Simulation Heuristic," *Judgment Under Uncertainty: Heuristics and Biases*, D. Kahneman, P. Slovic, and A. Tversky, eds., Cambridge University Press, New York, NY, USA, pp. 201–208.
[18] Gentner, D., 2002, "Psychology of Mental Models," *International Encyclopedia of the Social and Behavioral Sciences*, pp. 9683–9687.
[19] Gentner, D., and Stevens, A., 1983, *Mental Models*, Lawrence Erlbaum, Hillsdale, New Jersey, USA.
[20] Finke, R., Ward, T., and Smith, S., 1992, *Creative Cognition*, MIT Press, Cambridge, MA.
[21] Goldschmidt, G., 2001, "Visual Analogy: A Strategy for Design Reasoning and Learning," *Design Knowing and Learning: Cognition in Design Education*, C. Eastman, ed., Elsevier, San Diego, CA, USA, pp. 199–220.
[22] Gorman, M., and Carlson, W., 1990, "Interpreting Invention as a Cognitive Process: The Case of Alexander Graham Bell, Thomas Edison, and the Telephone," Sci. Technol. Human Values, **15**(2), p. 131.
[23] Roozenburg, N., and Eekels, J., 1995, *Product Design: Fundamentals and Methods*, John Wiley & Sons Inc., Chichester, West Sussex, UK.
[24] Finke, R., 1990, *Creative Imagery: Discoveries and Inventions in Visualization*, Lawrence Erlbaum Associates, Hillsdale, New Jersey, USA.
[25] Jansson, D., and Smith, S., 1991, "Design Fixation," Des. Stud., **12**(1), pp. 3–11.
[26] Forbus, K., 1996, "Qualitative Reasoning," *The CRC Handbook of Computer Science and Engineering*, A. Tucker, ed., CRC, Boca Raton, FL, USA, pp. 715–733.
[27] Trickett, S., and Trafton, J., 2007, "'What If:' The Use of Conceptual Simulations in Scientific Reasoning," Cognit. Sci.: A Multidiscip. J., **31**(5), pp. 843–875.
[28] Trickett, S., and Trafton, J., "The Instantiation and Use of Conceptual Simulations in Evaluating Hypotheses: Movies-in-the-Mind in Scientific Reasoning," *Proceedings of the 24th Annual Conference of the Cognitive Science Society*, W. D. Gray, and C. Schunn, eds., pp. 878–883.
[29] Newell, A., and Rosenbloom, P., 1981, "Mechanisms of Skill Acquisition and the Law of Practice," *Cognitive Skills and Their Acquisition*, J. R. Anderson, ed., Erlbaum, Hillsdale, NJ, pp. 1–55.
[30] Schrage, M., 1996, "Cultures of Prototyping," *Bringing Design to Software*, T. Winograd, ed., Addison-Wesley, Reading, EUA, pp. 191–205.
[31] Whitney, D., 1992, "State of the Art in Japanese CAD Methodologies for Mechanical Products-Industrial Practice and University Research," The ONR Asia Office Scientific Information Bulletin, **17**(1), pp. 89–111.
[32] Chanowitz, B., and Langer, E., 1981, "Premature Cognitive Commitment," J. Pers. Soc. Psychol., **41**(6), pp. 1051–1063.
[33] Dougherty, D., 1992, "Interpretive Barriers to Successful Product Innovation in Large Firms," Org. Sci., **3**(2), pp. 179–202.
[34] Olson, G., and Olson, J., 2000, "Distance Matters," Hum.-Comput. Interact., **15**(2), pp. 139–178.
[35] Olson, G., and Olson, J., 1991, "User-Centered Design of Collaboration Technology," J. Organiz. Comput. Electron. Commerce, **1**(1), pp. 61–83.
[36] Whittaker, S., and Schwarz, H., "Back to the Future: Pen and Paper Technology Supports Complex Group Coordination," *Proceedings of the CHI '95 Conference on Human Factors in Computing Systems*, ACM Press/Addison-Wesley Publishing Co., pp. 495–502.
[37] Ullman, D. G., 2003, *The Mechanical Design Process*, McGraw-Hill, New York, NY.
[38] Sommerville, I., 1997, *Software Engineering*, Addison-Wesley, Wokingham, England.
[39] Amabile, T., 1982, "*Social Psychology of Creativity: A Consensual Assessment Technique*," J. Pers. Soc. Psychol., **43**, pp. 997–1013.
[40] Schunn, C., Lovell, M., Wang, Y., and Yang, A., 2008, "Measuring Innovative Apples & Oranges: Towards More Robust and Efficient Measures of Product Innovation," Studying Design Creativity conference, Aix-en-Provence, France.
[41] Kirk, R. E., 1995, *Experimental Design: Procedures for the Behavioral Sciences*, Thomson Brooks/Cole Publishing Co, Belmont, CA, USA
[42] Kraut, R., Fussell, S., and Siegel, J., 2003, "Visual Information as a Conversational Resource in Collaborative Physical Tasks," Human Comput. Interact., **18**(1), pp. 13–49.
[43] 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.