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Cognitive Hindrances to Learning Mechanical Design*

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Engineering design is commonly taught by pacing student teams through design projects while teaching open-ended problem solving methods. This strategy addresses curricular content, but may not fully support students' cognitive learning needs in design. The purpose of this study was to explore the cognitive hindrances mechanical design students experience while learning design. A class of 29 students in a junior mechanical design course provided learning journal reflections during the semester on teamwork and learning design. These data on learning design were coded to surface cognitive hindrances. Common cognitive hindrances included a lack of design language, an unstocked repertoire, the unreliability of the imagination, and fixation throughout the design cycle. Based on the nature of these hindrances, we offer implications for teaching design courses.

Keywords: design cognition; design education; engineering design; communication; imagination

1. Introduction

Tribus argued "the central activity of engineering, as distinguished from science, is the design of new devices, processes and systems" [1]. Becoming adept at design *is* the culmination of engineering education. However, though design is the ultimate goal of engineering, how and what to teach in design is also the center of much controversy. Evans, McNeill, and Beakley asserted 22 years ago:

> The subject [of design] seems to occupy the top drawer of a Pandora's box of controversial curriculum matters, a box often opened only as accreditation time approaches. Even "design" faculty—those often segregated from "analysis" faculty by the courses they teach—have trouble articulating this elusive creature called design [2].

Little has changed in the ensuing decades; design curriculum matters are still unsettled [3]. However, within this controversy, some common educational trends have emerged. The engineering design process is typically taught as a rational step-by-step process, with frequent iterations or loops [4]. In this context design thinking is presented as an open-ended problem-solving process. Further, students are commonly assigned to small teams and given an extended design project on which to learn how to design.

Since this structure of teaching design is so pervasive, it is relevant to find ways to improve learning within this structure. One first step in improving design teaching would be to identify hindrances to learning that students encounter on design projects. The intent of this qualitative case study was to develop a thick description of such hindrances that could be transferable to similar contexts. Such understanding could inform design instructors how to adjust their teaching to increase learning within the own courses.

2. Background: known learning challenges in design courses

Learning to design is typically conceived of as learning two complementary topics: *design thinking* which is employed while following a *design process.* Design thinking is a problem-solving approach applied to the myriad of open-ended problems encountered while creating a design. This problem-solving approach involves first defining criteria a solution must meet, then generating alternative ways to achieve a solution, and finally applying the best alternative solution [4]. The design process is similar to design thinking, but on a larger scale; the process structures the entire project as one extended open-ended problem to solve. The design process involves setting design goals, generating and selecting a concept to meet those goals, and subsequent design detailing, prototyping, and testing [4]. Whereas design thinking may be applied to problems that take an hour to solve, the design process is applied to a project that extends over multiple weeks or months.

Students in design courses are usually assigned to small teams and given a design project that spans multiple weeks to months. The topics of design thinking and process are presented as the project progresses. This course content is supported by typical design textbooks [5–7].

One expectable learning challenge for the students is the open-ended nature of design problems.

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The bulk of other courses in an engineering curriculum teach analysis [4]. These courses develop solutions to well-structured (though at times difficult) problems. Typically, these solutions can be mastered step-by-step and applied in the same fashion. In contrast, design problems are ill-defined and the familiar routine of step-by-step learning and application does not work. The learners' difficulty is more than simply learning a new topic; it is adopting an approach that is not merely step-by-step toward a solution. The design process is messy, unexpected, and full of surprises even though the process can appear tidy [8].

Another known challenge is that the students must learn about the product they are designing while they design it [8, 9]. Since many design decisions are at first provisional, their product knowledge is also provisional and subject to change. As in any learning context, misconceptions can be incorporated with correct conceptions. These misconceptions in the students' understanding of their own design can be quite robust and interfere with understanding how best to proceed with the design work [8].

A further challenge involves applying knowledge from other courses (e.g. manufacturing processes or solid mechanics) to their design project. Indeed, applying analysis coursework can be an explicitly stated objective. However, transfer of knowledge (in this case transferring *the application* of knowledge) from one context to another can be very difficult [10]. It may be more difficult because analyses embedded in design problems can present themselves in an unstructured way, rather than as a typical end of the chapter homework problem.

A final known challenge relates to working and learning in teams. Design classes are frequently the first time students work in an authentic engineering teamwork context. Engineering science courses do not teach teamwork, nor do other previous academic experiences. Some students do have limited prior experience working in groups. However, unlike group work, professional teamwork is highly interdependent and relies on mutual support, collaboration, and focus [11]. Additionally, prior academic experiences rarely teach teamwork skills such as active listening, negotiating consensus, decomposing work into tasks, integrating individual effort into a joint work product, or assessing and managing one's own team's processes and relationships.

3. Context of this study

This research was conducted in an intermediate level Mechanical Engineering design course of 29 students. This course followed a typical engineering design course structure and used a common textbook. The students were assigned to intact teams of four for the semester. Each team designed, built, and tested three separate machines. Each machine was developed in two phases. The first phase developed an initial design, built a prototype, and tested the prototype (proto 1 phase, hereafter denoted P1). The second phase (P2) modified the design, built a second prototype, and tested the prototype. We used this approach for two reasons. First, although following a prototype cycle with a subsequent redesign prototype cycle is not typical of engineering courses, it is standard practice in industry. Second, students learn from prototypes and we wanted to maximize that learning [12–14].

To fit this many iterations (six total) within a 15-week semester, quick fabrication techniques were set by the instructor. The first two machine designs were constructed of corrugated cardboard using hot-melt glue. The first machine design removed poker chips individually from a chute, flipped them, and created a stack. The second machine alternately removed differently colored poker chips from two separate chutes, flipped them, and created a collated stack.

The third machine automatically loaded two colors of marbles into patterns on metal trays. The machines were fabricated from CNC plasma-cut sheet steel, formed, and assembled with prescribed hardware. Pneumatic cylinders with computer programmed valves were used to supply the motion. At the end of the course, a design competition was held and student designs were graded on the speed and accuracy of loading trays (function) as well as how manufacturable and assemblable the machines were.

4. Data collection and methods

Mid-semester each student was required to post five learning journal entries on the course web-site. In each entry, students were asked to describe something specific they had learned from an experience in design or teamwork. The students were encouraged to include anecdotes and rationale for their insights. During the final week of the semester each student was required to post three concluding entries. The 236 posted entries were the data used in this study. Two-thirds of these entries (155) described aspects of design, while the remaining primarily discussed insights on teamwork.

We chose qualitative methods for this study because they are well-suited for exploring unanticipated phenomena in naturalistic settings, in this case unanticipated cognitive hindrances in this design class. Our goal was to begin to describe and understand students' experiences as they learned design [15–18]. Qualitative methods effectively meet this goal [15]. Further, since little is currently published about the individual and cumulative effects of students encountering hindrances in design, an exploratory and descriptive approach seemed best [15].

Qualitative research employs many methods. Since this research explored the experiences of students in a design course, we selected a case study approach. Case studies examine bounded, integrated systems [16, 17, 19]. The students within this course form the bounds of the case.

However, a case study method does not specify how the data is to be coded. Since the data consisted of written learning journal entries, we chose content analysis to code for manifest (i.e. obvious) themes [15]. The design entries were initially read to discern the presence of hindrances. Based on this initial reading, we identified provisional categories for various hindrances that had surfaced. We then individually read the entries to refine the categories and more fully code the data. After this coding, we compared and discussed our individual assessments. This process was iterative and required each entry to be read and discussed approximately four times. Once hindrances were identified we worked to create a thick description of them, using the cognitive literature as a lens. Since design is highly cognitive, this theoretical lens seemed appropriate.

To triangulate we used two methods. First, two researchers were involved in coding all data and consensus was achieved regarding category placement and interpretation of individual entries. Second, the researchers were from widely differing disciplines (leadership studies and mechanical engineering). Both of these methods are standard practices for creating triangulation [16, 19].

To further understand the hindrances, they were interpreted through the lens of the cognitive literature. Qualitative results are typically reported as quotes and/or excerpts of the data, generating a more narrative structure than is common in quantitative methods [16]. Thus, we have supplied these data excerpts below. In addition to identifying the reported hindrances, most entries included the student explanation of the hindrance.

The aggregated student journal entries are a partial window into actual hindrances the students encountered. Though each individual posting is anecdotal, manifest themes developed from multiple independently posted entries describe phenomena operating at some level within the case. As such, the results present hindrances the students encountered, but will not identify hindrances the students were unaware of or were reported far less frequently than they occurred.

5. Results

We identified four major cognitive hindrances that students experienced: (a) the imagination is unreliable, (b) a lack of design language, (c) an unstocked repertoire, and (d) fixation. Each one of these hindrances formed a significant obstacle. However, when combined, as they often were, these hindrances were much more difficult for students to overcome.

5.1 Limits of the imagination

Imagination plays a large role in design since everything that is designed must first be imagined. By imagination we mean the ability, or abilities, to predict or foresee aspects of the prototype before it is physically realized. Three themes related to imagination emerged in the student journals: Students imagined completely successful prototypes, students ignored physical constraints while imagining their prototype functioning, and imaginative visualization had limited capacity.

To begin, the students had difficulty imagining the amount of problems their designs would have. They had strong expectations that their initial designs would work very well and were often surprised when their first prototypes did not work.

> It was made quite clear [in lecture] that what works in your mind, does not always transfer into reality. . . . We [however] thought that our machine would work flawlessly in the beginning but inevitably there were design errors that we did not foresee.

> The ideas that are in your head do not usually work out as easily as you would think. I have learned that your mind almost only sees the success in designs and it is very hard to predict where and what the failures will be.

Part of the course content emphasized identifying failures and potential failures. Prototypes were always diagnosed. Ishakawa failure diagrams (fishbone) were introduced as a means to systematically identify and chart possible failure modes. Yet, the students frequently expected *their* design to work as conceived. One student offered this explanation of why design problems could creep in unnoticed.

> With every idea, there are always more ways to make the device fail than there are to make it work. Any oversight, even some very minor ones, can result in a useless product.

Oversights are quite expectable early in the design process simply because the ideas are provisional and hence incomplete. These provisional ideas form a sparse schema about the design; the students deepen their schemas as they develop their design [8]. Any misconception introduced early in a design could progress to a robust misconception through rehearsal. Rehearsal is the cognitive process of moving short-term memory into long-term memory by repeating a thought with elaboration [20]. Further, rehearsal is strengthened by intervals of time between rehearsals. Since the design work extended over several weeks, early misconceptions could become quite robust.

Students also noted how they would ignore or overlook known physical constraints while imagining how their designs would function. This altering of physical constraints took many forms. What is striking is how blatant some of these alterations were.

> When thinking about a design in your head you can easily have "laws of nature" work how you'd like and not how they really do.

> Everyone knew that we [were] working with cardboard, however, when it was time to produce our chip flippers, many teams expected the cardboard to behave like finely machined steel. . . .

These oversights went unchallenged in their imaginations and yet many would be easily challenged by their own experience. The students each had 20 years of lived experience with the laws of nature and had passed college physics and engineering dynamics. The students were literally touching, cutting, forming, and gluing cardboard yet their imaginations did not identify strength on narrow sections as a problem.

This imaginative characteristic of overlooking known information could be an artifact of attentional resources being concentrated on one aspect of the design to the neglect of another [20]. In other words, as a student focuses on solving a design problem, the cognitive resources to identify that a physical constraint is being ignored may not be available, thus causing an imaginative lapse.

The third limitation of the imagination is related to a *limited capacity* to visualize. This ability to visually imagine a feature of a machine as part of the design process is critical. One must be able to imagine how parts will fit together or how they dynamically interact to create a successful design. Students routinely encountered difficulties using their imagination in this way.

> I have found there is a lot of need for mental vision. . . . Seeing something work in your head before anything is ever built or put together is what I consider to be mental vision.

> Our minds can only visualize so much. . . .

Cognitive psychology refers to "mental vision" as imagery, which is defined as "mental representation of objects, events, settings and other things that are not immediately perceptible to sensory receptors" [20, p. 532]. Cattaneo, Fastame, Vecchi, and Cornoldi argued that imagery is an active process in problem solving [21]. They further described a link between the use of imagery and creative problem solving, noting "visualization facilitates innovative solutions and clearly leads to novel and inventive discoveries" [21, p.112]. In this case, limits to the students' imaginative visualization abilities hindered their design work.

5.1.1 Virtual models can mislead

Closely related to limited visual imaginative capacity is how virtual artifacts, based on the imagination, can be deceptive. Students were required to create 3D solid models of their prototypes using *SolidWorks®*. Students struggled with creating virtual models directly from their imagination. As a result, some students created rough cardboard models first and then moved on to *SolidWorks®*.

> Although we had an idea of what the overall shape and size of the machine was going to be it was hard to implement that exact idea in SolidWorks®.

Students also encountered difficulty using the 3D models to predict how their design would behave. Just as they had difficulty early in the design process with imaginative oversights, oversights continued to persist when working with 3D models.

> It is important not to totally rely on SolidWorks® for assemblies. Just because SolidWorks® can easily assemble something does not mean that it is actually easy to put together in actual solid form.

Virtual modeling provides a means to study and evaluate designs. However, students seemed to forget they were working with models and not the actual product in real space. Thus, when misconceptions arose, based on the models, students did not recognize them.

In summary, the students' imaginations were limited in several ways. Their imaginations overpredicted success while overlooking failure modes. The laws of nature were suspended by their imaginations as were some examples of experiential knowledge. Their imaginative visualizations were also limited in ability and when 3D models were created the models could conceal imaginative lapses.

5.2 Lack of design language

The process of design in a team environment is, at its heart, a communicative process. Team members must know how to explain their concepts, negotiate meaning, and make decisions [22, 23]. But Bucciarelli noted that design is a "social process awash in uncertainty and ambiguity" [22, p. 221]. Thus, while good communication is required for good design in a team environment, achieving that communication may be difficult. The students noted their struggles with communicating, negotiating, and understanding concepts clearly.

> An idea is something that is in your imagination, and the translation barrier between your imagination and other people's is a big one.

> We all have different visions for this machine. More than that we have four different ideas for each part of the machine.

> Many of our ideas are quite scattered and the four of us are not yet on the same page. I feel like if I were doing a solo project on this I would have a good working model and the other three in my group would too, but all four would be different. Who am I to say my idea is better?

Design also requires ambiguity, at least at the outset as ideas are being generated [24]. Yet ambiguity, needed for exploring the design space, is not the same as miscommunication or misinterpretation. Miscommunication and misinterpretation should be prevented as much as possible if a good design is to result [25]. The students did not note much ambiguity, but they did note miscommunication and misinterpretation.

> The disagreement was nothing more than a miscommunication and both group members were saying the same thing but in different words.

The opportunities for miscommunication and misinterpretation are legion. The speaker's own idea may not be clear to them (ambiguity) and their description may not reflect their interior image. They may use the wrong vocabulary or grammar, be inconsistent, or unclear. Yet, in contrast to Weigers's et al. argument, on occasion miscommunication was leveraged into good design, or possibly a poor idea was negotiated into a better one [25].

> I have noticed multiple times now that a [bad] idea will be miscommunicated into a good one.

One has to speculate, though, what would have happened with good communication.

Bucciarelli argued that each discipline has its own "object language," which includes paradigms, technical terms, and physical artifacts, such as sketches [22]. In short, an object language includes a discipline-specific world view and everything that could be used to communicate within it. Different classes of engineers, such as electrical and mechanical, will have different object worlds, which will hinder their ability to communicate clearly on interdisciplinary teams.

Students can gradually acquire their own object language through coursework, but this method can be uneven at best, since some students are more adept at picking up implicit information than others [26]. One difficulty for students is that their object language occurs in their native tongue, in this case English. Since they are speaking English, they expect communication to be easy. Further, people with different educations, or different conceptual worlds, will describe shapes differently [25]. Thus, the students' inability to communicate clearly is expectable, yet makes their task all the more difficult.

> Trying to explain a part, or having a part explained to you, solely in words is almost impossible.

> Routinely one of us will come up with an idea, and then try to explain it and the team will imagine something almost completely different.

> When sharing ideas, come prepared with complete plans, thoughts, and ideas, so the only difficult part left is communicating it and not understanding/rethinking/communicating all at once.

The source for these difficulties was that students did not have the communicative tools they needed. They were still acquiring (we hope) their object language. They often lacked the accurate vocabulary for describing shapes, relationships, and movement. Since they were still learning their object language, communicating accurately among themselves was difficult. Given that verbalization was difficult, we anticipated sketching ideas would work better. Unfortunately, this was not the case.

5.2.1 Sketching

The students also noted difficulties using sketching to convey ideas. Sketches are a part of Bucciarelli's object language and thus each discipline has its own conventions for sketching [22]. But beyond being part of learning the discipline's language, sketching also serves several other useful functions for students.

Bilda, Gero, and Purcell reported that visio-spatial working memory is limited when dealing with imagery alone [27]. Trying to work with a design without any physical representation taxes cognitive resources. Thus, it becomes difficult for even seasoned experts to work with a complex design using imagery alone. For students, sketching would be crucial.

Sketching also supports the necessary dialogue between object and designer(s) [26–28]. It leaves a record of provisional thoughts along the way that may need to be revisited. For many designers, it functions as a type of speech and allows one to explore ideas more fully [27].

Students were encouraged to sketch but struggled to use this means to convey ideas. They noted shortcomings in their sketches.

> Often the sketches leave out important details such as where and how parts connect to each other and where special conflicts may occur.

> I have found that I need to take more time to sketch out my preliminary ideas. . . . My proper hand drawings are usually of good quality, but my quick sketches are not.

Stacey, Eckert, and McFadzean noted that sketches, while very important, can also be a source of confusion. "Misinterpretation of sketches is a major cause of communication failure" [29, p. 1]. One of the difficulties lies with trying to convey provisional ideas with a concrete sketch. Sketches convey decisions that have been made and ones that have not. The ideas left out can cause as much trouble as the ones included. Another difficulty is poor sketching skills [29]. Some students decided to address this problem by completing quality drawings before team meetings. However, Stacey et al. noted that creating quality drawings can lead to more emotional investment in ideas that are still provisional.

In summary, the students had many difficulties communicating their design ideas to their teammates. These difficulties arose from their lack of a discipline-specific object language used to describe shapes, relationships, and movement in words and sketches. Compounding this problem, the ideas the students were communicating were provisional and hence simplifying details in sketches generated ambiguous meanings.

5.3 An unstocked repertoire

Schön described experts as having rich "repertoires" [26]. These repertoires consist of examples, images, understandings, and actions that range across the domains that form the expert's expertise. An expert's repertoire is built over time from knowledge and experience until it is full and rich. In contrast, the repertoires of novices (students) are relatively empty, as several students noted.

> I started to find out we still lacked experience. Even though I had the desire and willingness to make the best product, doesn't mean that I could. First I had to gain more experience and knowledge. . . .

Certainly, the primary purpose of a design class is to begin stocking the students' repertoires with knowledge and experience in the design domain. However, students also noted lack of knowledge in complementary areas needed to complete the design.

> I've never really examined an assembly line. (*automation*)
>
> We, as a group, designed a part with dimensions that were not manufacturable. (*manufacturability*)
>
> Since this was our first time working with sheet metal, we were inexperienced with the tolerancing and the bend radii, etc. (*sheet metal as a material and process*)
>
> I didn't quite understand what the word prototype really meant until . . . I learned . . . that a prototype is something that functions and works. (*prototyping cycle*)

This lack of knowledge and experience was quite expected. Indeed, it was why this course was in the curriculum. Yet students also noted some other aspects about stocking their repertoires that were more unexpected. Students appeared to need concrete examples and actions in order stock their repertoires.

> In this case we were given a list of materials we could use for our project. The problem is feeling a list doesn't really help me. I need to feel and see the materials in order to fully understand their capabilities as well as their limitations.
>
> Getting into the shop to fix our own parts was really beneficial and almost to an extent needed in order for me understand what needs to be accounted for. . . .
>
> I'm more of a tactile person so things are easier for me when I have something concrete to work with.

Students also struggled with more intangible knowledge as well. Experts are skilled at knowing when a design is fundamentally flawed and must be abandoned [26]. Students were unable to discern when to "fish or cut bait" with their designs and pursued fixes long after an expert would have turned to another idea.

> You have to know when you have put enough time into something and start over.
>
> There has to be wisdom in deciding which issues are important to address, which to neglect, etc. Some of this wisdom can be natural but a lot of it seems to come from experience and trial and error.
>
> There are so many alternatives when it comes to design that it is difficult to choose the best path to take, especially since it is almost never obvious which path that is. This is the hardest part for me because I always end up second guessing my decision.

The students struggled with unstocked repertoires in several ways. Expectably, they were unable to access knowledge and experience they needed, but did not have. In response, they noted needing to stock their repertoires with hands-on learning rather than with textbook information. They also struggled with the overall meta-process of design. Fortunately, as they mature in the discipline, these hindrances will ease. This reality is not the case with fixation.

5.4 Fixation

Smith defined fixation as "something that blocks or impedes the successful completion of various types of cognitive operations, such as those involved in remembering, solving problems, and generating cognitive ideas" [30, p.16]. In short, fixation means that one cannot move beyond one's original set of ideas. Youmans noted that designers will fixate on features of preexisting designs or examples and develop new designs that are similar [13].

Several factors are thought to cause fixation. In paradigmatic thinking, one uses the same approach for solving a problem as one has always used for solving problems of the same class. This approach fails when the problem has significant differences from the perceived class that one does not attend to [30]. A second common cause is that one's implicit assumptions about the problem are incorrect. Implicit assumptions are difficult to surface and difficult to address on one's own [30]. Finally, recently encountered ideas can block or constrain the creativity of subsequently generated ideas. In this case, providing examples to give students a start on the problem may actually hinder their creativity, rather than support it [30, 31]. Students noted fixation effects throughout the design cycle.

> The first ideas that you have is not always the best idea, and oftentimes you can get stuck thinking only about that initial idea.
>
> After you arrive at a first prototype, improving it can sometimes be difficult for the designer. This is because we have tunnel vision, and feel that our design is the only way.
>
> Our first idea is the hardest thing to change. Instead we constantly fix it in our heads. . . . It's hard to just throw everything out and come up with something better or different than your initial concept.

Design fixation is difficult to address since it occurs unconsciously and designers may be completely unaware they are copying or barely adapting previously encountered ideas [13]. Yet unlike several of the other hurdles, fixation does not disappear as students become more experienced. Professional design engineers also suffer the effects of fixation [31]. Indeed, Jansson and Smith suggested that education and professional experience could predispose one to particular types of fixation.

6. Implications for teaching

Learning to deal with the hindrances identified in this case were not part of the stated course curricula. They did not appear on the syllabus, they were not framed as learning outcomes, development against them was not directly tested, and the design textbook did not address them. These hindrances simply fell below the radar. However, these hindrances significantly deterred students from learning design. Consequently, simply refining the current curriculum in this course would not address these needs. Rather, strategic additions or changes to the curriculum need to be made. Since the studied class is fairly typical of design courses, it seems reasonable that these same problems are fairly widespread and strategic changes to those courses also make sense. The following recommendations recast the hindrances as perspectives for design instructors and offer some possible teaching approaches.

6.1 Revisiting the imagination

The students' imaginative lapses spanned the entire design cycle in areas such as visualization, predicting failures, dynamic predictions, manufacturability, and physical properties of materials. These lapses seemed to be a cognitive effect and not simply the result of poor teaching, ineffective curricula, or lack of rigor on the students' part. A first step toward addressing these lapses is simply to recognize them in the same way that fixation is commonly discussed topic in design courses. A second step may be to reconsider what is taught about imagination. Whereas creativity methods are taught as a way to set the imagination free, perhaps methods for reining in imaginative flights of fancy also need to be developed.

6.2 Addressing the lack of a design language

The students encountered difficulty in describing parts as well as creating clear sketches. These impediments adversely affected working in teams and were particularly pronounced as the students worked with preliminary ideas. Many mechanical engineering programs teach little sketching and no discipline-specific object language. Since both skills are needed for effective teamwork, they should be explicitly part of the curriculum. Instruction and practice in informal sketching of impromptu ideas coupled with discipline-specific vocabulary could properly equip students. This instruction could build on Wiegers' research methods [25].

6.3 Choosing repertoires to stock

Design courses will inevitably reveal unstocked repertoires; consequently, supporting learning in complementary repertoires is necessary. The implication for design teaching is that considering the entire palette of what students must learn is crucial. For example, part fabrication process details are not part of a design course per se, but will in many cases be something the students need to learn. In this specific study, the instructor intentionally decided that prototypes would be made of sheet metal parts because the manufacturing process is more easily understood than other processes, such as machining. Another consideration is how to stock various types of repertoires. Some students noted that handling materials and fabricating parts was the only way for them to learn. Certainly, this sort of practical experience underlies an expert's repertoire and is easily implemented in a design course.

6.4 Addressing fixation

Overcoming fixation is an implicit part of the large national movement in the United States to teach creativity. We do not have additional insights about fixation that are not already part of this discussion. However, this study identified fixation effects through all phases of the design cycle and on problems of all sizes. The current trend to teach creativity methods usually frames fixation as a problem in ideation, that is, the very early phase of design. Since fixation is a cognitive effect that can hinder any phase of design, reframing fixation as a more pervasive difficulty is appropriate in the national discussion.

7. Conclusion

Four major hindrances to learning mechanical design were identified in this study: lack of design language, an unstocked repertoire of complementary knowledge and skills, the unreliability of the imagination, and fixation throughout the design cycle. The lack of design language became evident when the students had difficulty communicating design ideas on their teams. These difficulties impeded the general progress of design work and added uncertainty. The students' unstocked repertoires of knowledge complementary to design work, such as not understanding fabrication process limitations or lacking an intuitive sense of material properties, added difficulty directly to designing such parts. The students' imaginations were central to designing parts and assemblies that didn't already exist, and yet these same imaginations led students to overlook problematic designs, suspend the laws of physics, and/or simply believe what couldn't physically work would work. Fixation on design solutions occurred at every phase of the design, not merely during the early ideation portion.

These cognitive hindrances increased the difficulty in learning design as well as making teamwork more difficult. Individually each hindrance was significant and when combined, as they were in this case, their effect was also combined. Thus, effective instruction of design also needed to include instruction in how to deal with these hindrances.

These findings are limited by the case in this study. A different set of prerequisite courses and experiences could have modified the hindrances. For example, if the students had significant prior training in impromptu sketching and verbally communicating design ideas, peer to peer communication on design teams would have been improved and idea generation may have flowed more easily. However, inasmuch as design courses are intended to integrate several aspects of a curriculum into a whole, these or similar hindrances should be expected.

Further, the structure of this design class and its position within the curriculum is fairly typical of many engineering programs in the United States. As such it gives a fairly representative picture of the challenges design students face. However, if the curriculum is substantially different, or if students are not working within design teams, then the effect of the hindrances would be different as well.

To conclude, as noted earlier, while the design curriculum is still unsettled, the overall structure of teaching design has coalesced, at least within the United States. There is much to recommend in this current structure. However, this current structure requires strong supplemental support for students' learning as they encounter the cognitive hindrances that naturally ensue. Our hope is that as the community of design educators identifies the prevalence of significant cognitive hindrances they will seek ways to support student learning as these novice designers encounter these hindrances.

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