Examining Beginning Designers' Design Self-regulation through Linkography

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Abstract

Design process representations often attempt to show the iterative pattern of design through a circular or spiral representation. Expert designers iterate, constantly refining their understanding of both the design problem and solution. In other words, a designer's ability to manage the design process—plan, reflect, and incorporate new insights—may be indicative of proficiency in design. When first ideas do not work, these abilities can be leveraged to learn from failure and generate new solution attempts.

Despite instruction and representation indicating the cyclical nature of design processes, beginning designers often work in a step-by-step, regimented way. Among beginning designers, reactions to failed ideas are wide-ranging: some positive and some negative; some leading to action and some leading to apathy; some toward dedication and some toward disinterest. In short, how the designer frames failure experiences can determine whether or not each experience will be a benefit to their learning and final design. In light of the disconnect between beginning designers' capacity to manage failure in design iteration, further study of the cognitive processes of beginning designers as they encounter failure is needed to strengthen design education.

This case study describes patterns of self-regulation used by high-school design students as they navigate failure and iteration in a five-day design challenge. We present a framework that aligns constituent parts of design—analysis, synthesis, and evaluation—and phases of self-regulation—forethought, performance, and self-reflection. Furthermore, instances of failure or success in these cyclical phases are identified. Then, using think-aloud data from a pair of design students, linkography is applied to represent the process as a network of interconnected actions while designing. Connections forward and backwards in the design process are interpreted as instances of forethought or reflection.

The linkographic representation of the design process, corroborated with analysis of documentation in design journals and design artifacts, supports conclusions regarding the self-regulation strategies of beginning designers. Though contextualized and limited to one design team, the account of these designers is a useful starting point for coming to understand how beginning designers experience failure in design. These findings also offer insight into the design of educational experiences where failure may occur.

Introduction

Design problem-solving is invariably part of everyday life [1, 2] and design thinking is being increasingly adopted to solve problems in a range of disciplines. At its core, design is the process of developing solutions to complex problems; design takes place in circumstances that have multiple solution paths and dynamic problem and solution spaces, and do not have right or wrong answers or immediate feedback on solutions [3, 4]. Subsequently, design requires redesign when ideas do not work, or do not work as well as expected. Jonassen [4, p. 80] specifically noted that design problems "require greater commitment and self-regulation by the problem solver" than other types of problems. Related to the resiliency necessary for success in design, expert design has been characterized as fluency among different activities in design [5], repeated movement between detail and overview [6], persistence regardless of ambiguity [7], and a cyclic evolution of understanding for both the problem and potential solutions [8]. In other words, a designer's capacity for self-regulation—that is planning, managing, and reflecting on their work—can be considered a crucial element in fostering their ability to learn while designing and develop design expertise.

Conversely, inconsistent responses to failure while designing illustrate a gap between beginning designers' abilities and the reflective conditions necessary for design proficiency. In early design experiences at the elementary school level, beginning designers have shown a wide range of responses when their ideas did not work [9]. Some students returned to the design process or engaged in failure analysis—both considered a positive response. Yet other students gave up, lost interest, or moved on haphazardly, without planning or reflection—all considered negative responses. In other syntheses of design behaviors, beginning designers were found not to value iteration as much as they did with more experience [10], meaning fewer attempt may be made to improve ideas.

Even experiencing failure, by itself, does not necessarily mean that learning will occur; how the experience is framed will determine whether it results in learning. Evidence suggests that learning can be realized by working through failure in open-ended problem solving and by helping students investigate underlying principles and attempt multiple solutions [11-15]. The preparation of designers requires both experience, and opportunity to identify and integrate the lessons learned for future practice [6]. Therefore, examining the seeming disconnect between the nature of design—requiring failure and iteration and reflection—and the behavior of beginning designers—often acting counter to these behaviors—is necessary to inform design education. An increased understanding of students' failure experiences and responses while designing can be used to shape pathways for the development of design expertise.

The purpose of this case study was to describe the use of self-regulation strategies among high-school design students as they navigated failure and iteration in a five-day design challenge. This work was guided by a theoretical framework which integrates design (including judgments of failure or success) and Self-Regulation Theory [16], which is described in the next section. Afterward, the case context, information sources, and analysis approach are described. We treat the design experiences of a single team as illustrative of design and self-regulatory responses [17], and use think-aloud data and linkography [18] to portray the teams' forethought and reflection in design. Finally, we report the linkographic results, interpretation, and implications for fostering self-regulation in design practice.

Theoretical Framework

Observations of beginning designers suggests a consistent inability to identify salient details, frame the design space, and suitably improve ideas [19, 20]. The iterative nature of design is intended to capitalize on early design ideas, successful or not. However, this iteration requires attention to features of the design and environment. One can imagine how an attentive student may enact design—with careful confidence building based on the results and lessons learned from past project, the establishment of challenging goals and a strategy for approaching the problem, monitoring throughout the project to ensure an appropriate trajectory, and reflection to synthesize the experience afterwards. These aspects are among the constituent parts of Self-Regulation Theory, which was integrated with design to form the theoretical framework of this work.

Self-regulation is "self-generated thoughts, feelings, and actions that are planned and cyclically adapted to the attainment of personal goals" [16, p. 14]; Self-Regulation Theory structures attention prior to, during, and after performance into three phases. As in design, these phases are cyclical, where information and thoughts shape behavior proactively and reactively [21]. *Forethought* encompasses activities and thought in preparation for a task, such as planning, goal setting, and non-cognitive factors like self-efficacy. In *performance*, attention is given to the quality of execution by self-control and focusing strategies, as well as record keeping. The final phase, *self-reflection*, includes judgment and reaction elements that assess and explain outcomes, as well as shape future attempts.

Self-regulation has been recommended as an avenue for inquiry on student learning from failure. When testing contexts that led students to fail, and encouraged exploration of underlying concepts for productive learning, Kapur and Bielaczyc [12, pp. 76-77] explained:

> There is some indication from the group discussions that the productive failure design [of instruction] gave students opportunities to engage and develop their meta-cognitive and self-regulatory functions, which in turn are critical components of learning and problem-solving expertise…. Examining the collaborative problem-solving processes to unpack the roles of meta-cognitive and self-regulatory functions in productive failure is an area that future studies would do well to examine further.

This recommendation for research touches on the need for self-regulation to be paired with contextual factors for specific learning objectives.

We paired self-regulation elements with simplified features of design—analysis, synthesis, and evaluation [22-24]—to form a framework for regulated responses to design failure (Figure 1). Analysis may be thought of as the front-end of design, including identifying the problem and gathering information. It is divergent, expanding the problem-space and information available. Synthesis is a convergent phase of design, aimed at processing information to produce a solution. Evaluation includes judgments of the design product to determine whether it is deemed a success or failure and continues towards reactions about the design. In the framework, failure is a pivotal component, connecting previous cycles of design and self-regulation to future cycles. To arrive at a solution there are repeated stages of construction and evaluation. Therefore, each design attempt may be thought of as a cycle of self-regulation. Ideally, through subsequent iteration, both self-regulation and designed solutions will become more sophisticated.

Seen through the call for inquiry about self-regulation and the lens of this theoretical framework, we focused on qualitative inquiry of students' experiences throughout design, and how these might be connected to judgments of failure or success and then future iterations. The attention to failure experiences herein is maintained by the case study approach and use of multiple information sources to build understanding of the connected contexts wherein failure occurs.

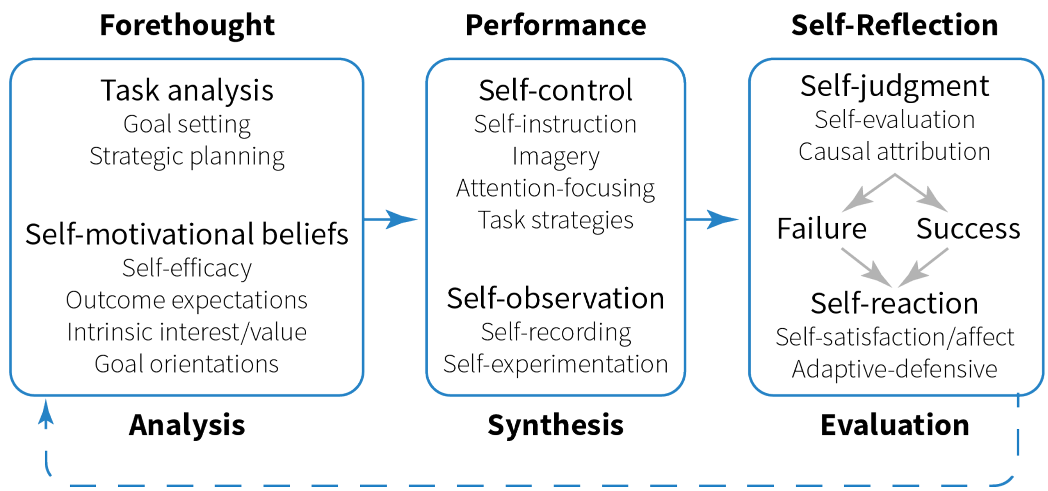


Figure 1. Theoretical framework for regulated responses to design failure.

Methods

Case Context

This close examination of students' design work was situated in one implementation of a 9th-grade curriculum unit exploring soft robotics. Soft robotics uses compliant, soft, and bioinspired systems to solve robotics problems [25]. The field of soft robotics is interdisciplinary [26] and young [27]; therefore, by introducing new paradigms and materials for robotics, the unit was conceptualized to increase interest and dispel student misconceptions about engineering. Our previous work has described the design-based evolution of the curriculum experience and instructional materials in the "Soft Robotics to Broaden the STEM Pipeline" project (DRL 1513175) [28-31]. In its present iteration, the lesson and design challenge span 5-7 days (of 90 minute classes) and includes instruction on pneumatic principles and fabrication instructions to make an entirely soft, air-powered robot end effector, or gripper, as a design team. Students are presented the challenge to design a soft robotic gripper for use in an agricultural operation (Figure 3). Then, students are supported through an iterative process of exploration, information gathering, and testing on soft robotic fingers, before making predictions and attempts at a completed soft robotic gripper (Figure 2).

Unique to this context, and intrinsic to the two-part silicone elastomers used to fabricate the grippers, this design challenge required holistic iteration, where student teams created a new design for each phase rather than tinkering with the previous attempt. Additionally, due to the pneumatic actuation of these grippers, success and failure are evident—either the gripper inflates functionally or it does not. In each repeated phase of design, students had the opportunity to manipulate the configuration of their gripper and the fabrication process, to overcome failure modes and improve the performance of their end product.

Design Problem: Worldwide there are more people eating and fewer people producing food; we need to be more efficient and not damage what we have. You have been hired to design a robotic gripper to help a small farm operation be more efficient in picking up fragile produce. They have several different crops but their main yield is tomatoes about the size of a golf ball. Your gripper needs to help a farm worker accurately pick up the crop and sort it, all without damaging the food. Gripper should pick up, hold and release the tomatoes (golf balls). You should also be prepared to give training on your gripper and explain your design decisions (why you made it the way you did). Document your work using your electronic Engineering Design Journal.

Specifications

1. The robot gripper must be able to pick up a golf ball by inflating with the squeeze bulb pump.
2. The gripper must be able to securely hold the golf ball for 5 seconds.
3. The gripper must be able to release the golf ball by opening the air valve.

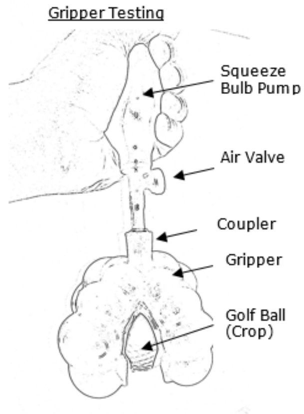


Figure 3. Design brief for soft robot design curriculum with gripper demonstration sketch.

Figure 2. Iterative curriculum sequence for designing and refining soft robot fingers, then designing and improving soft grippers.

Participants

Using a purposive sample, to “maximize what we can learn” [17, p. 4], two students were selected and invited to engage in this research as a design team. First, the teacher Mr. Gray (all names are pseudonyms) was chosen for his past participation in the broader soft robotics study, and therefore familiarity with the design context, as well as his willingness to host the in-class observations and research for the case study. Mr. Gray began the soft robot design lessons in his classroom and moved to a nearby laboratory space as students began fabrication stages of design. Students worked individually on conceptual phases of design, before forming a team to share their ideas and proceed with fabrication. The day-to-day structure of class included a question prompt and discussion, before a teacher-led briefing on the day's objectives. Once working, the class proceeded through the project fairly autonomously; the teacher monitored progress and was available to answer questions.

Given considerations from van Someren, et al. [32] that participants in think-aloud studies should be cooperative and able to verbalize thinking, Sydney and Jordyn may be ideal case study subjects to observe. On an initial Situational Motivation Scale [33] survey of students before the lessons, Sydney reported lower motivation than the rest of her class, however both girls ended the design challenge with average motivation relative to their peers. Over the course of five days of observations, the girls generated ideas, conducted research, fabricated three finger prototypes, and made four attempts at a complete gripper.

Information Sources

Several information sources from the design process were reviewed and triangulated to capture the design experience and students' self-regulation strategies: in-person observations with audio recording and field notes, design artifacts (design journals and soft fingers or grippers), and a follow-up interview (see Table 1). During each day of the research, students were asked to say what they were thinking out loud; the nature of collaborative discourse in design naturally elicits these types of speech [34, 35]. Subsequently, think-aloud studies have been used frequently in design and self-regulation to approximate thinking for both individual- and team-based analysis [e.g., 7, 19, 36-38]. Both students wore a microphone, and their verbalizations reflected time thinking on their own and as a team. Recorded conversation still included down-time and off-topic conversation, therefore the audio recordings were edited to retain conversation germane to the design task (whether it was individual or collaborative), and then transcribed. Field notes were based on description and reflection [39], and were also used to describe results since video recording was not permitted. Notes were hand-written, then digitized and summarized immediately after the observation period. In order to observe students' natural strategies and reactions for failure, the observer interfered as little as possible and withheld questions to the follow-up interview.

Two types of design artifacts broadened the perspective offered by the word-for-word recordings. Students' day-to-day work was self-recorded in design journals that were used for assessment in the classroom, and also provided to the researchers. Given the timing of the course, in the second half of the course, students were familiar with the process of design documentation, and even referred to past projects to remember the necessary steps. Supplementary evidence of the team's work, including soft robot solution attempts, were kept as demonstrations of the design process and an embodiment of success or failure. Handling these artifacts was helpful for augmenting and verifying the audio recording [40].

Last, about two weeks after the soft robot unit, students were contacted by video conference to corroborate the researchers' account of the experience and uncover additional details not directly observed. Interviews, therefore, served as a member check and opportunity to garner additional insight "going beyond the goal of ensuring that the 'researcher got it right'" [41, p. 844]. The interview was semi-structured and asked about the experience generally, approaches during the design process, and specific design test results. While discussing the design process, images of the design artifacts were provided as stimuli.

Table 1. *Summary of Information Source Quantities.*

Design Team	Observations				Design Journal Pages	Follow-up	
	Days	Full	Edited	Transcript		Interview	Transcript
Sydney + Jordyn	5	6:13:27	3:09:54	99 pages 32,336 words	12	0:17:55	5 pages 1970 words

Note: All times are recorded as H:MM:SS.

Analysis

Compared to previous quantitative analysis of the soft robot experience and other investigations of design failure, a strength of this study was the holistic, embedded consideration of the design experience. Data collection and analysis included multiple days of *in situ* recordings, as well as accompanying information that provided a wealth of information to analyze (Table 1). A synopsis the team's iterative attempts was made by a cursory review of the transcript and field notes—each design prototype and attempt and repair attempt was identified as a milestone in the design process which might catalyze reflection (aligned with the theoretical framework of this work). Using the language of students' judgment—from audio recordings and follow-up interviews—students' design tests were characterized as a success, partial success, or a failure (adapted from [42]).

Next, linkographic analysis was performed as a means to quantitatively describe and visualize how the design unfolded (see Figure 4 and [18]). Linkography portrays connections in the design process visually, and is based on a chronological sequence of *design moves*, and their connections, *design links*, in contrast to other methods that code and categorize design behavior. Each move was defined as "a step in the process that changes the situation…. a step, an act, an

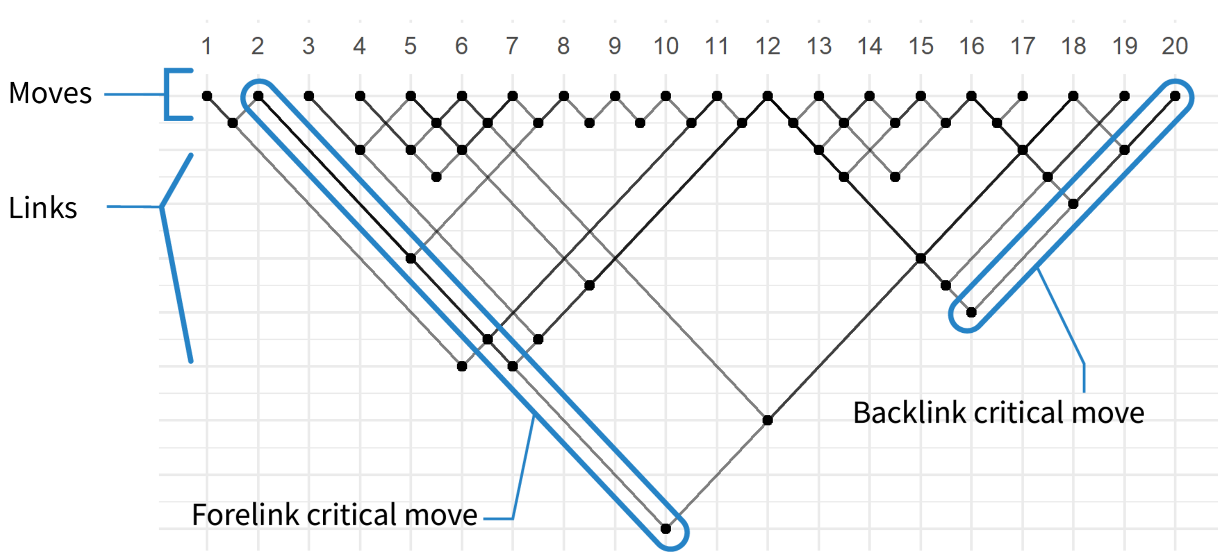


Figure 4. Example linkograph showing forelink critical moves and backlink critical moves.

operation, that transforms the design situation" [18, p. 42]. Design moves were identified by the first author, using examples adapted from past research and a codebook for consistency—for example, transformations of the idea or elaboration of an idea both constituted new moves [43]. Due to challenges of reliability for segmenting design moves [44], moves were identified using conceptual summaries of the design process as it fit the definition of a design move. Developments in the process were summarized and put in order to create the sequence of design moves. As a result, and like previous research, the inferred design moves are chronologically fit, though not aligned word for word with the team dialog [18]. Design links were identified by recursively examining each pair of design moves, based on common sense and the first author's familiarity with the design context [45]. Guidelines in previous research informed a codebook creation for links, and supported consistency—for example, ideas with the same "chain of thought" were linked [46].

Other metrics culled from linkographic data include the *link index*, which indicates the degree of integration throughout the design process (found by dividing the number of links by the number of moves) and *critical moves* (found by a tally of the links to a given move) [18, 34, 45]. The identification of critical moves in linkography has corresponded to the findings of other types of processes assessment and suggest the creativity and usefulness of that design step for forward movement, "thrust" [47], in the design process. Linkography has been used in a number of settings to make sense of the complexity of design, including the evolution of ideas in brainstorming [43, 48, 49]. Two analogies emerge from the structure of a linkograph, which connect to the self-regulatory theoretical framework specific to this paper (Figure 1): the forward-looking links in the design process are representative of planning behaviors (forethought) and the backward-looking links are representative of reflective behaviors (self-reflection).

Linkography Results

By applying procedures for linkography, we portray the design process visually [50] and complement the representation with description of key features of the process—an analytical approach which can be labor intensive [47]. Indeed, cognitive information from the design process was a mass of information. Sydney and Jordyn made numerous design moves, with an increasing number of possible links among them. Each nth design move added the possibility for $n - 1$ additional links to be evaluated. For transparency in the process we acknowledge the challenge of analyzing such a large amount of data. However, by use of a codebook, triangulation through additional information sources, and review of the results by design educators and researchers, we maintain the quality and trustworthiness of the results.

Sydney and Jordyn had 1,433 design moves over the five days of observation (a total of 1,026,028 possible links; Table 2). Among these moves, 2,889 links were identified for a link index (density) of 2.02. The link index was within the expected range relative to past research, for example, [18]. The team had links in both directions, with the proportion being equivalent to that found elsewhere: about two-thirds [50]. Most design moves related to past events of the process (backlinks only), with few moves being forelinks or orphans (no links). Orphan moves tended to be ephemeral statements inspired by the project, but unconnected to the normal stream of thought.

Design moves were not evenly distributed by day, nor were they linked evenly by day (Table 3). The first days of class were a sense-making process, becoming oriented to the design challenge. A lower move count, and higher link index for Sydney and Jordyn's first day is suggestive of this tentative exploration. Furthermore, the first day of the activity was foundational for two reasons: it included individual work before the team united, and included foundational instructions (e.g., the introduction of the design challenge) that were built upon by the instructor in subsequent days. As the team began working together on Day 2, they made many connections to their individual work on Day 1. Later days connected most heavily to this first day or the day just previous. This pattern suggests that information cascaded through the design process from day to day, but that design ideas were revised in the course of the project. For example, on Day 3, Sydney and Jordyn did prototype testing of their soft robot fingers, and exhibited links back to their design configurations and predictions of success on Day 2. In the final day of the project, the link index increased again; this corresponds to the team's multiple attempts to finish the project and refine their design.

Table 2. *Linkographic Metrics for Sydney and Jordyn's Design Process.*

Descriptive Metrics	
Total Design Moves	1,433
Total Links	2,889
Link Index	2.02
Possible Links Considered	1,026,028
Link Directionality	
Backlink Only Design Moves	396 (27.6%)
Forelink Only Design Moves	35 (2.4%)
Bidirectional Design Moves	979 (68.3%)
Orphan Design Moves	23 (1.7%)

Table 3. *Daily Design Moves, Links, and Relationships by Design Team*

			Links Between Days				
Day	Design Moves	Index	1	2	3	4	5
1	105	2.30	241				
2	407	1.71	160	698			
3	345	1.33	39	161	458		
4	252	1.48	16	54	80	374	
5	324	1.60	1	12	29	49	517

The identification of critical design moves is conducted by finding moves with a number of links greater than a set threshold; it is subjective and varies by context. With greater moves there are increased opportunities for connection, therefore a threshold that includes about 10% of moves is recommended [18, p. 58]. The label for critical moves denotes the direction of links with an arrow, for example identification of “<CM^4” is a move that connects to at least four prior design steps. Even with selecting only about 10% of moves, the collection still presents too many moves to analyze. However, each test outcome appeared as a CM^4> critical move—for prototypical finger testing or gripper testing, whether the design was successful or not. Each finger test was also included in the list of <CM^4 moves, signifying that the finger design and test results were a means to integrate prior planning, conversations about design variables, and predictions.

The linkographic representation of the team’s design process looks tangled due to the large number of moves and links, and the large span of many links (Figure 5). The connections among days are annotated with the instances of design tests—green for successful inflation and red for failed inflation and grasping. Based on observations and supporting evidence, several underlying patterns of the linkograph are manifest and offer information pertaining to self-regulation (planning and reflection) while designing.

Initial Sense-Making

The foundational beginning to the design process is illustrated in the linkographs as well (Figure 6)—showing forethought in self-regulation. Focus on the conceptual design phase, preceding any fabrication by the team, showed a concentration of links as the team set goals, discussed expectations for the project and their brainstormed ideas, and planned strategically. Individual thinking out loud included comments for goal setting, strategic planning, and self-motivation:

- Sydney mused about the project and anticipated how it would work: “This is the pump and the hands can attach to it. So then you inflate the joint. So then when you inflate the joints it grips.” (Sydney, Day 1)
- Jordyn brainstormed an idea to plan ahead: “I’m going to start drawing my first idea that’s based off of a human hand. When you look at your fingers, it bends at a couple different places.” (Jordyn, Day 1)
- Sydney also expressed curiosity and interest: “I’m curious to see how the gripper will hold something that’s not round because it looks like the joints only like… go circular.” (Sydney, Day 1)
- As the team began working together, they tried to integrate their prior work: “So how long do you think… How many joints? Do you think that’s long enough or do you want to do something?” (Sydney, Day 2) “Yeah, I think… like exactly that, to be honest.” (Jordyn, Day 2)
- The team also established a goal orientation that structured their process: “I mean, worst comes to worst we can fix it, change it, … fix it, change it, rearrange it.” (Sydney, Day 2)

The team started fabrication early, partway through Day 2, which left time for a large number of iterations later in the design process—they had time for adaptations in their approach. In the follow-up interview Sydney confirmed that “after the first finger…it was a lot easier to understand what you were doing.”

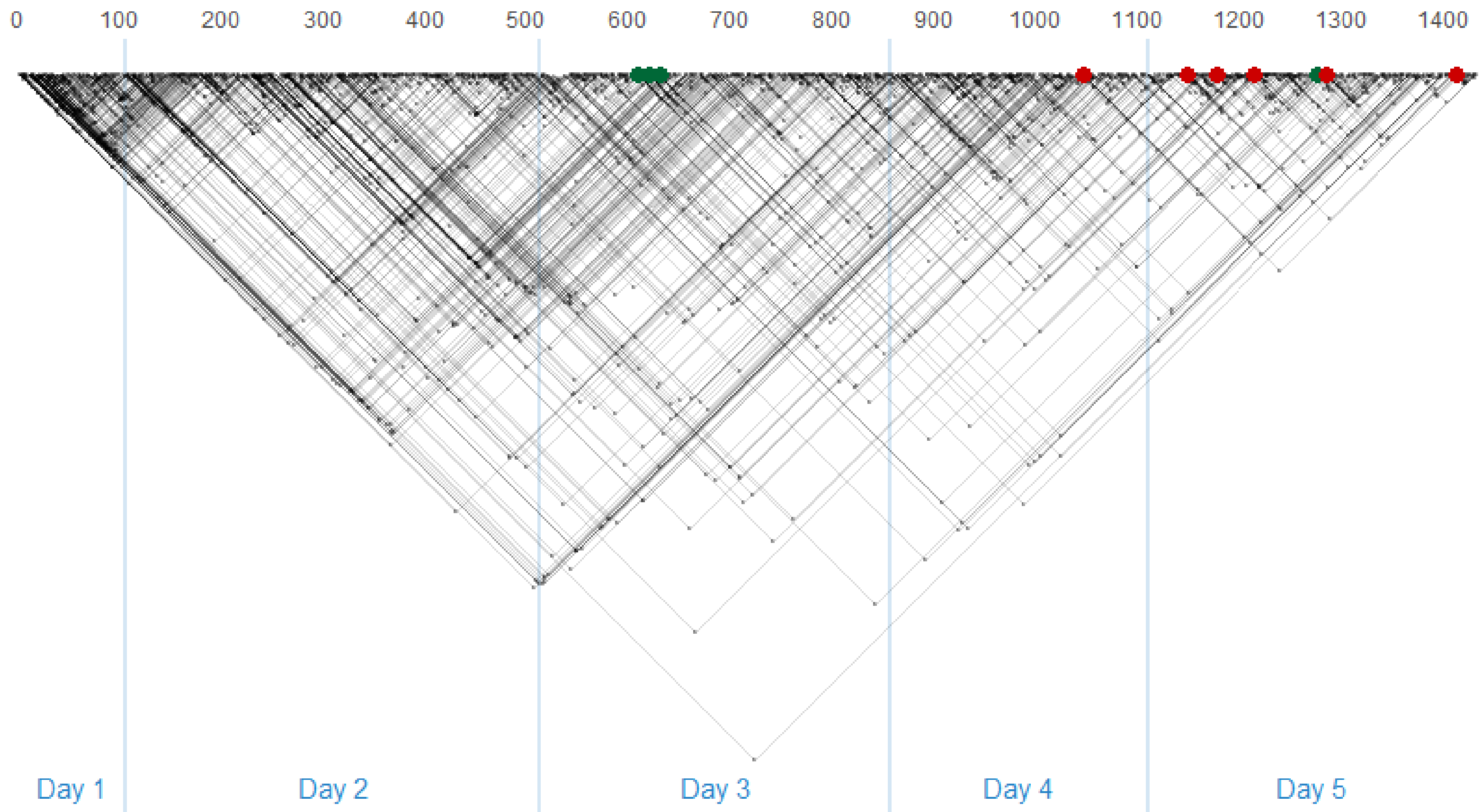


Figure 5. Linkograph of Sydney and Jordyn's design process over five days. Design testing outcomes are shown as failures (red) or successes (green) along the design moves.

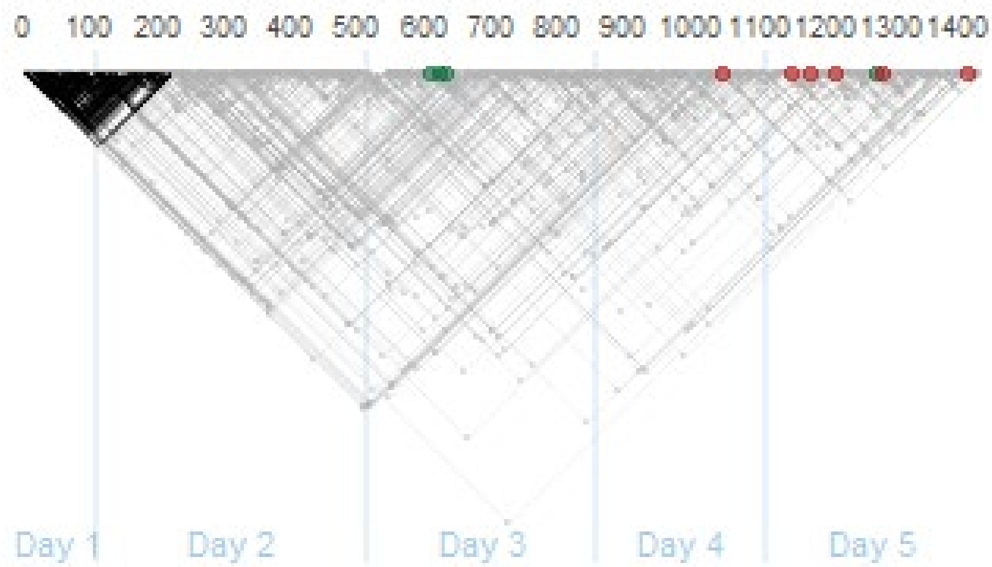


Figure 6. Emphasized linkographs showing conceptual design phase. The linkograph for Sydney and Jordyn shows an integrated conceptual design phase prior to fabrication.

Prototyped Design Tests

On the third day, Mr. Gray shared, "You're going to design, test, and create multiple ideas for your fingers…. So you can do fingers, based on those fingers you're going to make a hand." In this day the team completed their prototype fingers and discussed how to pivot that information to the final gripper design. The diagram provides a clear indication of when Sydney and Jordyn configured three different fingers and discussed the merit of each finger after testing (Figure 7). These were fabricated and tested successfully; then their conversation shifted to reflection. Their discourse referred back to the configuration of the designs and tried to attribute variation in performance to the variation of designs that had strategically been planned. A portion of their conversation gives context to this evaluative discussion.

- "So it might… the more joints might help to get around the objects. You can test the smaller one again if you want." (Sydney, Day 3)
- "All right, retesting the smallest one so we can compare it to the longer one. I kind of like this one, in that it has three joints." (Jordyn)
- "Mmhmm." (Sydney)
- "But I feel like it needs to be longer as well. And I also… I like this gap right here." (Jordyn)
- "Yeah, I think that our spacing was spot on with leaving the gap towards the center." (Sydney)
- "Yeah, exactly. So I think maybe like the length of the middle one." (Jordyn)

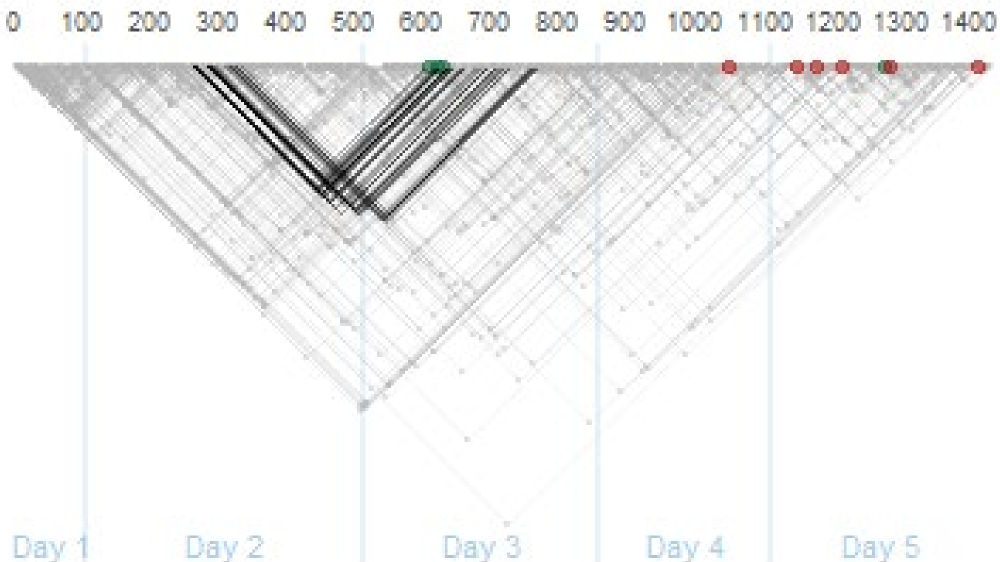
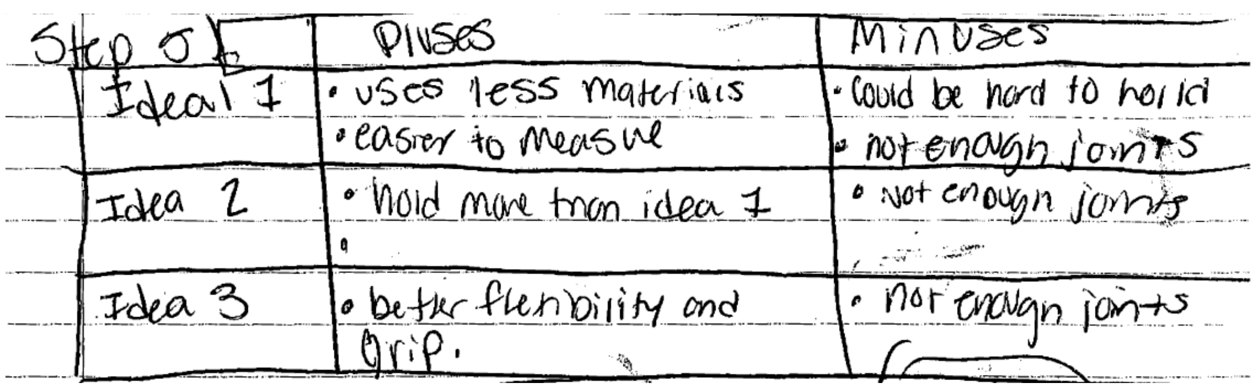


Figure 7. Emphasized linkograph (Sydney and Jordyn) of design planning and evaluation.

After the experience the team felt this was "probably the most successful part of the project" (Sydney, follow-up interview). Each finger inflated successfully and provided valuable information to inform the next phases of fabrication. Their design journals noted the pluses and minuses of the ideas, representing opportunities for iteration even among successful ideas (Figure 8).



Step 5	Pluses	Minuses
Ideal 1	• uses less materials • easier to measure	• could be hard to hold • not enough joints
Idea 2	• hold more than idea 1	• not enough joints
Idea 3	• better flexibility and grip.	• not enough joints

Figure 8. Design journal excerpt (Sydney) documenting pluses and minuses of prototype testing.

"Learning How to Complete the Project"

In the end of their design process, Sydney and Jordyn attempted to make several grippers, which each failed for a different reason (Figure 9). These occurrences of failure were included among the CM^4> critical moves because they were referenced in the discussion afterwards—as the team

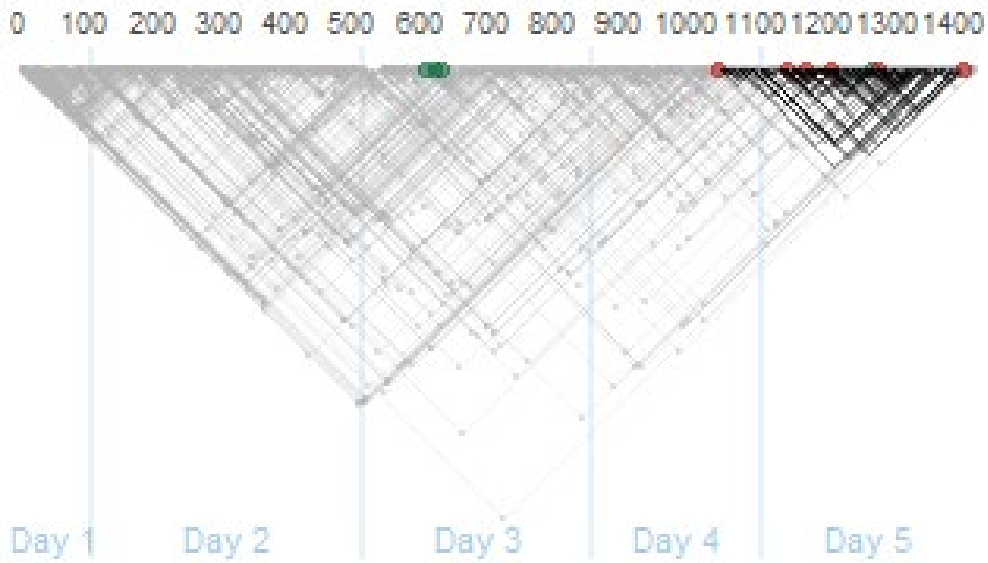


Figure 9. Emphasized linkograph showing attempts to respond to failure in gripper design.

tried to interpret what had occurred and how to move forward. Related to the self-regulatory framework of this work, iterations and future work were influenced by the test result, in combination with its attributed causes. For example, when the team encountered trouble holding their mold together, Sydney stated "the rubber bands we're using are not effective at all" (Day 3) and the team searched for new bands to use instead. And at the observation that the mold was bending, the change was "to try replacing a coupler of the parts to see if that fixes it" (Jordyn, Day 4). As the team identified what went wrong in each attempt, the source of error seemed to be fabrication precision (Figure 10); therefore, they focused on correct execution of fabrication steps instead of changing their design. For these two, failures increased their motivation to be

Figure 10. Fabrication flaws experienced by Sydney and Jordyn: 1) leaked mold leading to holes in the top surface (patched unsuccessfully); 2) poor adhesion between layers leading to leak on side; and 3) clogged air chambers leading to a rupture near air inlet.

meticulous in design; they were interested in learning through the project. However, they stated that learning how to complete the project needed to include more than just a successful gripper—"Because even if you get the block to lift up but you don't really know what you did, then that doesn't really help you" (Jordyn, follow-up interview).

Discussion

This study contributes to our understanding of how beginning designers think during design, especially during instances of failure. It demonstrates patterns of beginning designers in anticipation of failure and testing, and reactions to failure as it transpired. In order to foster self-regulation, several implications can be drawn from the experiences of this team.

First, the day-to-day implementation of the design challenge can be leveraged to support self-regulation during the design process. Structural aspects of the class impacted the design process of the team, as represented by linkography. For example, introductions and daily orientations from the teacher provided a daily reminder about next steps and were referred to by students during design work. Intentionally shaping class structures to model planning and reflection can be a means to foster self-regulation for students.

Second, providing an authentic project context, such as the fabrication of soft robotic components, was meaningful in supporting iteration and motivated students to find a design that worked. When the team's gripper designs did not work, they took opportunities for reflection and tried again repeatedly. Because feedback emerged from the context—either their design worked or it did not, with clear evidence from testing—students were able to discover underlying causes for success and failure in the fabrication of their grippers and work to resolve these in subsequent iterations. The commitment to iteration in this experience also speaks to the benefit of allowing multiple iterations. Rather than concluding the project with a theoretical plan for future work (i.e., "what would you do differently next time"), students were able to pursue multiple attempts at the final design, with lessons learned from each attempt.

Finally, this work provides evidence that formative assessment can meaningfully provoke reflection while designing. In the case of prototyped finger designs, the mid-project milestone provided an opportunity to integrate what had been learned so far and plan for the next phases of gripper design. In a contrasting case, when the team's ideas for their gripper didn't work, they repeatedly tried to manufacture a design without anticipating the errors that may occur. Design documentation was a common catalyst for reflection, as teams thought back about what they had done; however, questioning by the teacher or a design review could prompt similar design behaviors. Formative assessment of the design project may have been a way to encourage the team to slow down and work more intentionally on their designs.

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