Feedback in concept development: Comparing design disciplines

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Design feedback is an essential pedagogical tool to promote student design progress, yet little research has focused on what instructor feedback looks like, especially across design disciplines. In this paper, we analyzed feedback provided in dance choreography, industrial design, and mechanical engineering to explore variation in feedback type across disciplines as well as how feedback type encouraged students to take convergent or divergent paths in their design processes. Many common feedback types were observed across the three disciplines, regardless of variance in context and expectations, as well as some notable distinctions. With regards to feedback directing convergent and divergent thinking, feedback suggesting convergent pathways was more prominent across all three disciplines.

Keywords: design education, design feedback, design processes, conceptual design

Innovative solutions are often traced to ideation, where diverse creative ideas are initiated and developed (Brophy, 2001; Liu, Bligh, & Chakrabarti, 2003). Design processes facilitate this route to bringing ideas to innovative outcomes (Ottosson, 2001; Soosay & Hyland, 2004), and this path toward innovation hinges on successful concept generation, defined as the creation of multiple and diverse concepts (Akin & Lin, 1995; Atman, Chimka, Bursic, & Nachtman, 1999; Daly, Yilmaz, Christian, Seifert, & Gonzalez, 2012; Liu et al., 2003). Students often engage in design ideation during project-based courses such as cornerstone and capstone engineering design courses and domain-specific and interdisciplinary studio courses (Dym & Little, 2004; Oh, Ishizaki, Gross, & Do, 2012; Sagun, Demirkan, & Goktepe, 2001; Uluoglu, 2000). Project-based courses often allow for more freedom in timing and pathways, but instructors must make sure students stay on track. Instructor success relies, in part, on the ability to provide guidance and feedback on students' design paths and processes, allowing them to explore on their own, but facilitating a structure where the students can learn strategies to fully explore and define problems, engage in

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divergent processes by generating a wide range of solutions and converge on and verify the most promising outcomes.

In our work, we investigated instructor feedback in dance choreography, industrial design, and mechanical engineering to compare instructors' approaches to guiding students' work. While the content of the design projects was unique to the disciplines, students engaged in design thinking, as they were responsible for generating, evaluating, and developing ideas into a final design *outcome. Our goal was to compare feedback settings and types across disciplines and understand how instructors used feedback to suggest thinking pathways* (convergent or divergent) as ideas were created and developed, or did not direct students to either way of thought. By exploring feedback across disciplinary contexts, we aimed to understand disciplinary similarities and differences as well as provide a means to share coaching strategies across disciplinary boundaries.

1 Design education across design disciplines

Design is not associated with a single discipline or domain of knowledge in definitions or descriptions of design (Daly, 2008). Many disciplines engage in design thinking, even though they may each use unique language to describe it (Goel & Pirolli, 1992). There is considerable overlap in the work performed by choreographers (dance designers), engineering designers, and industrial designers as they are all engaged in design thinking in their iterative design processes. Design literature supports a broad range of disciplines in discussions of designers. For example, Nelson and Stolterman (2003) include architecture, educational design, engineering, industrial design, information design, instructional design, organizational design, software design, and urban design, and Zimring and Craig (2001) include architecture, computer science, engineering, industrial design, and the performing arts. Studies on design with multiple disciplinary design perspectives can provide rich results that allow for design disciplines to learn from each other (e.g., Cross & Roozenburg, 1992; Daly, 2008; Daly, Adams, & Bodner, 2012; Goldschmidt & Rodgers, 2013; Lloyd & Scott, 1994; Purcell & Gero, 1996; Yilmaz, Daly, Seifert, & Gonzalez, 2010, 2015).

Dance choreography is an act of combining elements to form a whole and translating ideas into artifacts (Schiphorst, Calvert, Lee, Welman, & Gaudet, 1990) and the design process is seen as a way of explicating and of modeling and expanding potential ways of thinking about making art (Schiphorst, 1989). In composing a new dance, a choreographer starts from a particular stimulus within a context or an event, and explores or develops the generative idea, or interprets the music or the narrative through movements that successfully reflect the theme (Lee, 1988). Choreographers are often engaged in a balance of imagination and analysis to produce 'something' regarding a sense of self, others, physical environments, and the expressive nature of embodied symbolic systems (Press & Warburton, 2007).

Engineering design has been characterized as combining scientific discoveries with principles targeted at useful products for bettering human life (Pahl & Beitz, 1996). It is "the systematic, intelligent generation and evaluation of specifications for artifacts whose form and function achieve stated objectives and satisfy specified constraints" (Dym, 1994a, 1994b). Innovative solutions with exceptional functionality are important to engineering organizations especially in times of accelerating change (Basadur & Finkbeiner, 1985). Expert engineering designers generate design specifications, and translate those design specifications to a final artifact by establishing objectives and criteria, generating alternatives, synthesizing, analyzing, constructing, testing, and evaluating (Sheppard & Jenison, 1996; Sheppard, Macatangay, Colby, & Sullivan, 2009).

Gotzsch (1999) defined the industrial design process as switching back and forth between functional aspects of design, and emotional and aesthetic aspects of design, depending on the type of product and the stage of the design process. Industrial designers are engaged by a range of clients to bring a fresh approach to age-old issues. They design not just commercial products, but also user experiences, processes, and systems. For example, an industrial designer might not only design a high-tech medical device for a hospital, but also the patient's interactive experience and touch points with medical staff in the emergency room. Similarly, industrial designers might work with retail merchandisers to reorganize store floor plans and re-imagine the in-store experience for potential customers (National Endowment of Arts, 2013).

2 *Divergence and convergence in design processes*

Design thinking involves complex cognitive processes requiring designers to ask diverse questions, explore the problem and solution space in depth, generate a variety of options for pursuit, and thoroughly develop and evaluate promising pathways (Dorst & Cross, 2001; Maher, Poon, & Boulanger, 1996). Designers move through cycles of idea development, narrowing, and more generation to eventually determine a final design. These iterations require divergent thinking for creating choices to consider, and convergent thinking for narrowing and selecting from those choices.

In concept generation, a variety of ideas is considered a key component of success where designers explore many different areas of the "design solution space" (following the notion of a "problem space" defined by Newell and Simon (1972)) (Jansson & Smith, 1991; Nelson, Wilson, Rosen, & Yen, 2009; Shah, Smith, & Vargas-Hernandez, 2000; Srinivasan & Chakrabarti, 2010). Novelty is also considered a success criterion where in this space of all potential solutions for a problem, designers create concepts that are not considered obvious (Dean, Hender, Rodgers, & Santanen, 2006; Linsey, 2007; Peeters, Verhaegen, Vandevenne, & Duflou, 2010; Shah et al., 2000). Self-imposed constraints or 'primary generators' influence ideas (Darke, 1979), and while all designers have first ideas, fixation on a first obvious idea prematurely closes the design space and does not leave room for novel ideas (Cross, 2001; Jansson & Smith, 1991; Linsey et al., 2010; Purcell & Gero, 1996). Pushing past the obvious ideas requires divergent thinking, which includes shifting perspectives, seeing new possibilities, being unconventional, combining the disparate, taking risks, and producing multiple answers (Basadur, Graen, & Scandura, 1986; Basadur & Hausdorf, 1996; Cropley, 2006; Runco, 1991, 1993; Silvia et al., 2008). While design processes often have a phase labeled "concept generation," concept generation happens throughout a design process, when one encounters a decision point and creates multiple ideas for options for the decision.

While divergent thinking is crucial to successful concept generation, convergent thinking is also vital as it determines the direction of the design embodiment stage (Guilford, 1967; King & Sivaloganathan, 1999). Convergent thinking refers to human cognitive activity that seeks a single or best solution through identifying familiar solutions, reapplying set techniques, and accumulating existing information (Cropley, 2006; Guilford, 1967; Runco, 2007; Weisberg, 1999). Convergent thinking is necessary to evaluate, synthesize, and select the most promising ideas, and ultimately the concept that will become the final design. Convergent thinking is also intimately linked to knowledge. On the one hand, it involves manipulation of existing knowledge by means of standard procedures, and on the other hand, its main result is the production of increased knowledge (Cropley, 2006). There are numerous approaches to concept selection in engineering, including intuition, feasibility judgment, multi-voting, numeric and non-numeric selection charts, pairwise comparisons, decision matrices, and prototype testing (Aurand, Roberts, & Shunk, 1998; Mullur, Mattson, & Messac, 2003; Otto, 1995; Pahl & Beitz, 1996; Pugh, 1996; Thurston & Carnahan, 1992; Ullman, 1992; Wang, 1997).

3 Role of feedback on ideation

Providing feedback is a foundational communication event between the instructor and designer or design team, providing knowledge about progress and adjustments needed in subsequent approach and behavior (King, Young, & Behnke, 2000) as well as actions taken by an external agent to provide information regarding some aspect of one's task performance (Kluger & DeNisi, 1996). Instructors act as mentors as well as mediators and managers for their students through the use of feedback (Taylor, Magleby, Todd, & Parkinson, 2001). Novice designers must learn when and how to shift through the necessary cycles of divergent and convergent thinking, and design instructors prompt these shifts through the way they structure their courses, assessment guidelines, and their feedback and coaching (Dannels & Martin, 2008; Tolbert & Daly, 2013). Instructor mentorship, which includes inspiring students to take ownership, fostering creative tension, and giving students the opportunity to fail as well as to succeed, has been identified as an essential element for successful capstone design experiences (Marin, Armstrong, & Kays, 1999; Pembridge, 2011; Stanfill, Mohsin, Crisalle, Tufekci, & Crane, 2010).

The nature of feedback and culture of the feedback structures can impact student direction and learning (Annett, 1969; Balzer, Doherty, & O'Connor, 1989; Book, 1985; Dannels, 2005; Dannels, Housley-Gaffney, & Martin, 2008; Dannels & Martin, 2008; Jurma & Froelich, 1984; King & Behnke, 1999; King et al., 2000; Kluger & DeNisi, 1996). For example, King et al. (2000), argued that variables such as the nature of information processing requirements for cognitive tasks (in terms of tasks that require high degrees of attention capacity versus tasks that can be executed mindlessly), direction of attention (whether the attention was on the task or on the self), and timing of feedback are vitally critical to the impact of the feedback on learning.

As design processes generally flow from divergent to convergent activity, greater pushes toward convergence are more likely as design processes progress. However, design process models represent smaller waves of divergent thinking throughout the process (Banathy, 1996; Cross, 2000) (See Figure 1); for example, in early design work, divergent thinking may entail suggesting many diverse ideas, but in the mid to latter phases, divergent thinking may entail suggesting multiple ways to achieve specific characteristics of the chosen concept. Even at the very last stages of design, decisions have to be made, and in those decision-making processes the possibility to be divergent exists by creating choices for how to accomplish final touches before the final choice is made.

Additionally, because iteration is such a key component in successful design (Adams, 2002; Atman et al., 2007; Atman, Cardella, Turns, & Adams, 2005; Cross, 2000), at the end of a design course, it is conceivable that an instructor could encourage students to think about what they would do if they had more time to iterate, e.g., where in their designs could they explore more options. Many questions remain regarding what role instructor feedback has in the different stages of design ideation and how feedback varies in terms of convergence and divergence across diverse design disciplines.

4 *Methods*

The data were chosen from a larger dataset provided by the Design Thinking Research Symposia organizers (Adams & Siddiqui, 2015) and included a series of video-recorded feedback sessions among instructors and undergraduate

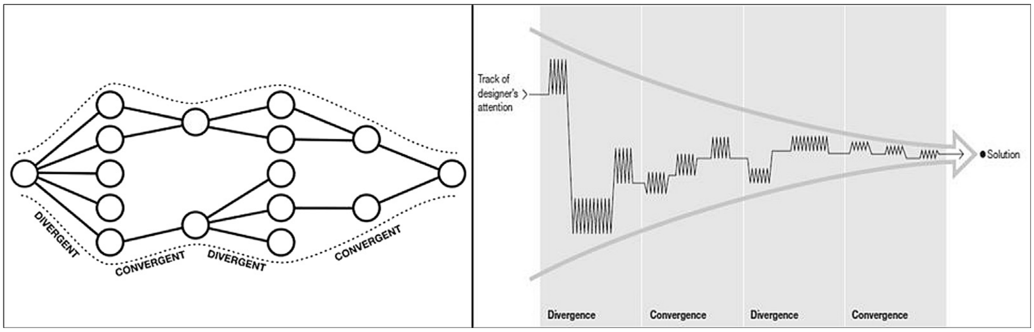

Figure 1 Design process models (Cross, 1994; Moore, 2009).

students in courses in dance choreography (CH), industrial design (ID), and mechanical engineering (ME). Research questions guiding our study included:

1) What feedback types are evident within and across disciplines?
2) How does feedback compare across disciplines?

4.1 Participants and settings

Participants included two undergraduate students in a dance choreography course, seven junior undergraduate students in an industrial design course, and fourteen senior undergraduate students taking a mechanical engineering design course. The CH and ID students were working individually and the ME students were split into three teams. The ID setting included an external client in addition to the course instructor providing feedback, whereas CH and ME included instructor(s) only for feedback sessions. The projects' durations varied among the three datasets: CH − 4 months, ID − 2 months, and ME − 4.5 months. The timeline of the projects in each discipline is depicted in Figure 2.

4.1.1 Dance choreography dataset

In the dance discipline, choreographing is the act of designing and a dance composition is the outcome of choreographing; thus we use 1) choreograph and design and 2) composition and design outcome/solution interchangeably when discussing the dance discipline to align with the language of the discipline and also to connect back to the design commonality across the disciplines.

In the choreography course, students worked independently to choreograph a dance composition for a public performance. The concept of the piece was that of the student's own choosing, and this concept could be modified throughout the design work as the piece took shape. Students created their own movement vocabulary and assembled the movements into a dance composition using choreography design tools. They were also required to select their performers, as well as manage sound, lighting, and costume design. They directed two

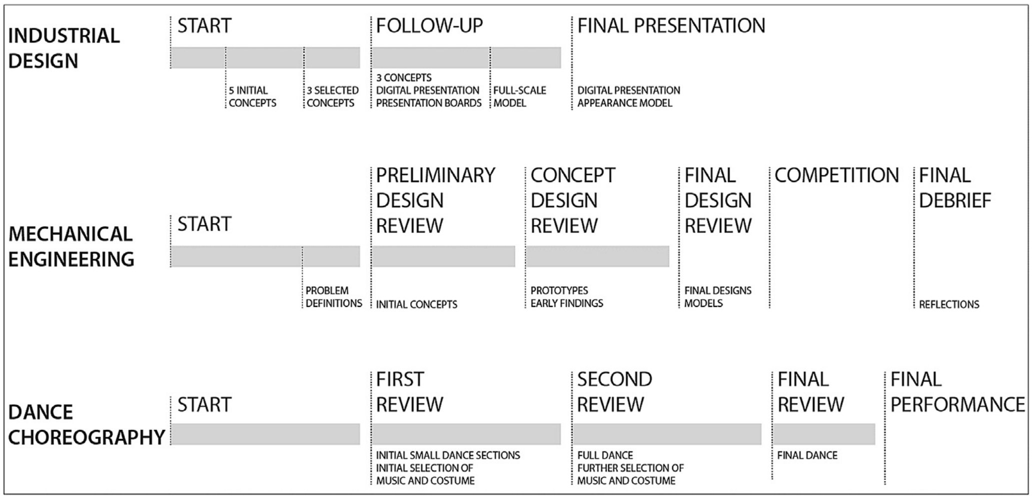

Figure 2 Timeline of the projects from each discipline

rehearsals per week, and presented their works-in-progress at three separate company showings.

After these company showings, students participated in reviews, in which five dance instructors provided feedback on the dance work. In the first review, instructors provided feedback on the small sections of the students' work that they showed in which students were exploring the concepts guiding their choreography and included an initial selection of music and costume. In the second review, the dance instructors responded to students' dance designs that combined small sections from the first review into a full dance work. The students were provided feedback on the synthesis of the dance elements into a full work and how the costume and music selections were aligned with the intentions and execution of the work. In the final review, instructors provided input on the full dance work presented by the students. All three of the review sessions for the two students participating were included in the analysis.

4.1.2 Industrial design dataset

The industrial design students worked on a sponsored project with an office furniture company that was trying to bring a new line of impromptu seating units to the market for individual office use and small meetings. They wanted the students to focus on bringing excitement into the office environment by approaching design concepts as accessories with color and emphasizing unique forms. Students were provided with design specifications, including shape, height, and size restrictions.

Students participated in five reviews throughout the project. In the first review, students met with the instructor for a desk critique, and were asked to decide on five concepts they would further develop. In the second review, students were asked to narrow down their concepts to three solutions to present to the client. In the client review, students presented their concepts to the client as well as the instructor, in front of their classmates. In addition to the instructor, students had the opportunity to gather feedback from the client. The fourth review focused on the evaluation of the full-scale prototypes of the chosen concepts, and in the final review, students presented both their appearance models and digital presentations of their solutions.

4.1.3 Mechanical engineering dataset

Three groups were formed to work on three different mechanical engineering design projects. Based on some initial information, students were asked to develop their own problem definition and justify their reasons for its importance in engineering. The projects included designing: 1) an aquatic robot that can swim and move like a fish in order to follow real fish in the oceans and study them in their natural habitat, 2) a device that would safely open jars containing hazardous materials, and 3) a lever that tows aircraft out to a runway. Funding was provided for prototyping if the students developed their budget plans and got approval from their instructor.

Three reviews took place with an additional debrief. All reviews were conducted by the instructor in front of the class. In the preliminary review, student teams developed their problem definitions and initial design concepts; however, this review was not included in the dataset, thus our analysis focused on the second and third (final) reviews. The second review focused on reviewing prototypes and early evaluation findings. In the final design review, students showed their final designs and prototypes to the instructor and were immediately graded. While our analysis focused only on the second and final reviews, an additional review took place to choose one team out of three to move onto a design competition with nine other teams. At the end of the semester, students were also asked to reflect on their projects and the class in general and identify the issues they faced with during building their prototypes.

4.2 Data analysis

The purpose of our analysis was to compare types of design feedback provided and feedback structures across the three disciplines and examine how the feedback suggested convergence, divergence, or neither. To determine types of feedback, we analyzed the entire data set using a using the constant comparison technique (Glaser & Strauss, 1967) and then refined again by comparing to the feedback typology developed by Dannels and Martin (2008). We then compared the feedback types and structures in each of the three disciplines, looking for commonalities and distinguishing features. We also analyzed how the instructor encouraged divergent thinking, convergent thinking, or neither type of thinking through the feedback. While divergent and convergent thinking are complex, we developed definitions to focus on a core idea of both types of thinking and to create a reliable approach to coding (Daly & Yilmaz, 2015; Yilmaz & Daly, 2014). We defined feedback as pushing toward divergent thinking if students were being encouraged to create choices for themselves. Feedback facilitating convergent thinking was defined as pushing students to make choices. Feedback that was neither convergent nor divergent was often asking students to develop their ideas without suggesting how that development should take place, i.e., whether students should create some options to consider and then decide, or to decide one way to achieve a particular goal and add it to the artifact.

5 Findings

We present outcomes of our analysis of feedback types and structures across the three disciplinary feedback sessions, with a specific lens on how the feedback suggested design thinking pathways to students (convergent, divergent, or neither). The section presents information on each of the disciplines separately and then discusses key similarities and differences.

5.1 Feedback in dance choreography

The feedback sessions in CH took place as a round table discussion with instructors providing feedback to students as well as each to each other, as instructors were also designing a dance piece. Students and instructors were trying to represent a main idea through their compositions, which required a lot of iteration on how to best use movement vocabulary and choreographic elements to represent that idea. Instructors provided reactions and suggestions to facilitate iteration. The instructors all participated in the reviews as they were also individual practitioners who were choreographing their own works. This structure created a setting where they provided feedback for both each other their students. Students witnessed how expert practitioners accept and integrate feedback from others into their compositions.

Feedback from instructors focused on the qualities and consistency of movements, vocabulary throughout the dance piece, the use of compositional tools like space and timing, and how the various subcomponents of the work, including music and costumes, provoked an emotional response. Feedback directed students in choosing design components, i.e., choreographic choices that maintained alignment with the essence (main idea) of the work. They suggested students focus on the design origin by asking them the mood or feeling their performances would portray to the audience and how the design elements supported or hindered that main idea: “I don’t get what that means so maybe a little more work on that. What is it to you? Is it a subway?” The most frequent feedback given by the dance choreography instructors was evaluating the quality of the artifact. The instructors discussed what they liked, i.e., what “worked” for them in viewing the composition, and what they did not like, i.e., what did not work for them about the dance and related elements. They also provided recommendations for how to fix what they perceived was not working but also suggested that students explore other ways to accomplish an aspect or suggested multiple ideas that students could explore.

5.1.1 Convergent feedback

During feedback sessions, instructors asked students to specify intentions and details of the artifact, i.e., the dance composition. These questions often directed students to engage in convergent thinking by requesting that they articulate their choice and the reasoning for it. For example, a CH instructor provided feedback that would require the student designer to clarify a movement vocabulary choice of their design: "I don't know if that was on purpose… I'm assuming your intention was the… scan." Instructors also provided feedback that aimed to keep students on track regarding the schedule and expectations of the project. Most of this feedback related to evaluating students' progress directed convergent thinking because it pushed students to focus on the end goal and finish their design artifacts. For example, a dance instructor reminded a student, "You have to be done before Thanksgiving!"

5.1.2 Divergent feedback

The instructors often suggested that students consider multiple ways of achieving a particular goal of the artifact. For example, "So it's important but to… play around with that. [W]hat are they … feeling when they do that? Is it like some kind of thing they just do or is it – are they having a secret whatever your story is," and "Play around with different hands, um, so what is it to you?" Divergent thinking was encouraged as the instructor gave students multiple ideas about where to start, and also modeled what different options could by providing examples of the types of diverse ideas students could explore. As a way to encourage students to explore multiple options, the instructors sometimes provided suggestions for what the multiple options to consider might be. For example, a CH instructor suggested: "I would play with timing or direction or placement of the stage space or other ways to, uh, surprise us…" Divergent thinking was encouraged as instructors gave students multiple ideas about where to start, and also modeled what different options could by providing examples of the types of diverse ideas students could explore.

5.1.3 Neutral feedback

During feedback sessions, instructors often prompted students to add more detail to where decisions were not yet made, emphasizing relationship of performers (in design language, subcomponents) relative to one another, the manufacturing (or realization) of the final piece and the assembly and disassembly of the artifact/performance. For example, one instructor identified aspects of movement vocabulary, space, timing, and the relationship among performers: “I think you want to take each of your ideas, you know your panic, your sleep, um, and the caution and find out what the essence of each of those are you know like movement-wise and texture-wise, how to use time and space and all those cool things that you’re already doing very well and you can maybe articulate your idea more that way by thinking about those elements, the essence of each of those ideas and then we’ll see more you know distinguishing characteristics of that.” The majority of the dance data included feedback on aspects of the choreography that were effective and ones that needed refinement. For example: “I liked how just the duet went back and [she] stayed out there by herself that surprised me.” Also, “The one part of the whole piece that didn’t fit for me was the foot, when the foot came out. It was funny to me, and it didn’t fit with the rest of the piece for me, it didn’t make sense.” In some cases, instructors also directly recommended specific changes to improve their performance pieces. For example, “Is there any way that her foot could pop out over a person’s shoulder up here? This was considered neutral feedback as students could explore how to improve the design as suggested by the instructor.

5.2 Feedback in industrial design

Overall, the instructor took a mentoring role with the students by offering suggestions and feedback throughout the entire process. The one-on-one reviews allowed him to respond to any questions students might have and helped them stay on task by offering scheduling suggestions. He pushed the students to make their own design decisions while showing various directions. He also put the students in the client’s mindset by helping them understand the importance of using materials and processes the client already has available.

Since the project was sponsored by an external client, the instructor challenged students to think as if they were working for the client and be receptive to the manufacturing processes and the appropriateness of the materials to be chosen. During feedback, the ID instructor often suggested multiple options for students to consider, recommended certain ways of doing things, and requested further elaboration on the initial concepts. In many cases, he relied on his practical design expertise to explain how a particular mechanism would work or what kind of material would be appropriate. His approach included providing options for students to consider, allowing students to explore these options on their own, and then asking for more elaboration on the ideas. He also often used feedback to question artifact quality, assess progress, and prioritize ideas. At times, he also suggested that his students stay away from complexity and continue with designs that were considered safe.

5.2.1 Convergent feedback

During feedback, the instructor prompted students to evaluate their ideas. For example, “Rate these in order of your preferences,” and “Which would you rather develop?" The instructor sometimes asked students to evaluate risks of their design options, and encouraged them to make decisions early to get a commitment to one idea that would be completed on time. This approach prompted convergent thinking as the instructor was trying to protect the students from failure (not getting the project done on time, the outcome not working properly, poor form, etc.). For example: "Cause you wanna do something kinda safe ..." and "We want to be able to get the biggest bang for the buck. And this is going to sell to more people and this is going to appeal to more people because it, it's got, it's got the different looks, but it's a simple form." Additionally, both the clients and the instructor challenged the students with clarifying questions, for example, "The piece that comes out, what did you envision the material was?" and "You're saying that there's just separation between the layers of plastic for storage?" In addition to feedback for clarification purposes, the instructor prompted students to make decisions about their ideas, for example, "Just a metal cylinder?" and "What if you were dealing with a two-and-a-half inch by two-and-a-half sections of upholstery?" This feedback suggested convergent thinking, having student clearly articulate a choice and the reasoning for a decision.

5.2.2 Divergent feedback

Throughout the design reviews, the instructor provided feedback to direct the students towards exploring solutions or alternatives. The instructor sometimes suggested students consider multiple ways of achieving a particular goal of the artifact. The instructor did not indicate specifically how to achieve the goal, but suggested that students "play around" with ideas. For example, to suggest a modification on the form of the seating unit's upholstery, he said, "Maybe you – what you do is you play – work backwards –from this." Divergent thinking was emphasized as the instructor told students they should consider possibilities before making choices about how to achieve their goals. Another approach observed was where the instructor suggested that students look at how others have accomplished similar designs and use them as inspirations. For example, the instructor suggested students analyze the existing furniture to explore how 'fun' could be integrated into designs: "But it needs to be… it has a great opportunity to be fun… Look at the Herman Miller… it's extreme, but … you could get some inspiration from it." When he encouraged this type of exploration, the implication was that students should consider multiple ways of accomplishing that particular goal and look externally to create alternatives. For example, "You gotta get online, look at how people are sitting in those things," and "This is a book… these are well-known designers who come up with something really unique and innovative, and… this just shows how they figured out how to make it… work, in other words, how to build them." This feedback pushed for divergent explorations as the instructors suggested that students think of other ways to achieve the goals of their projects, and gave students specific ways they could go about finding these other design options.

5.2.3 Neutral feedback

This feedback type did not clearly push the students towards convergent or divergent thinking. Elaboration on the details of the concepts was often asked as part of the feedback sessions in order to gather additional information on students' rationale for decisions, eliminate misunderstandings, or to prompt new areas to explore. This happened through questioning, e.g., "Tell me about the materials. What are you thinking about on this?" The instructor focused mainly on asking students to elaborate on the material choice and product dimensions, although there were cases where he provided feedback on the relationship of components to each other, how the product would perform, how it would be assembled and disassembled and would form modifications, e.g. "Now this might be hard for them to manufacture – you have to think about that." Relying on comparisons with other existing artifacts or elements in nature that resembled students' ideas was another strategy used by the instructor, for example, "Kind of like tinker toys, sort of modular."

5.3 Feedback in mechanical engineering

The ME feedback sessions were structured as team presentations where the instructor focused on questions about how the design would function and encouraged students to be specific on aspects of their designs. The instructor's feedback focused on helping students achieve a functioning outcome within the given timeframe, rather than pushing students to explore potential alternatives within the same solution space. Much of the instructor questions were focused on students' decision-making processes and clarification on their design artifacts. Design reviews were conducted as professional presentations, and thus seemed to have less room for conversation and discussion of ideas. The class seemed to be structured similar to an engineering business where the instructor was the project manager to make sure everything was working and each project was on schedule for final delivery.

5.3.1 Convergent feedback

Most of the feedback provided by the ME instructor suggested that students engage in convergent thinking to improve their ideas, such as asking students to specify design details, evaluate a variety of concepts, assess the project timeline and expectations, and analyze risk. He tried to help students narrow down their solution space by pushing them to achieve the objective of finalizing the concept that would meet the design criteria. The feedback sessions frequently included questions by the instructor to understand details of the concepts and reasoning for students' design decisions. The general structure was that students would present their concepts formally to the class and the instructor would ask for clarity to make sure he understood the details of students' concepts, for example, "How is that tail attached to the white – the white bar – the ABS?" and "Why do we do 90° one way?" Time management was especially prevalent in the ME instructor's feedback due to the necessity of the solutions functioning at the end of the semester. The instructor provided feedback to keep students on pace and reminded the class of the importance of the schedule, for example, "Why were we trying to get 'em last night as opposed to in the last three months?" Reminding students of time and pushing for students to meet deadlines would prompt students to make decisions about what concepts to pursue and to finalize details of those concepts, both of which are convergent thinking processes.

5.3.2 Divergent feedback

In the ME feedback data, divergent thinking was not evident. This might be due to a priority of the course on design analysis and decision making early on in the design process. Design Review 1 was not included in the data, so there is potential this review was focused on divergent feedback.

5.3.3 Neutral feedback

The ME instructor's feedback often encouraged students to be specific on aspects of their designs, for example, "Looking at that servo again … You might check that … with the relative position, and I realize the picture might not be accurate … But it looks like in an extreme location, I don't think it's going to work, but just check it to make sure." The instructor also focused on whether the artifact would function as it should be based on students' design decisions. For example, the instructor said, "I got two concerns. One is the water tightness of the, ah, PVC. I think you need to make sure you got O-ring seals because you're gonna have to go in and out of that a number of times. And so using RTB or, ah, silicone. Ah, it won't be too, ah, efficient for you if you have to pull it off… and then go in there and then reseal it and wait for it to dry and then pull it off." The instructor encouraged students to refine and iterate on areas where decisions were not yet made or where he questioned how well they would work. This type of feedback allowed students to decide their own paths for how to address the concerns.

Feedback from the instructor also included direct recommendations for change, for example, "You might want to think about moving the pivot point to the center of pressure so that movement arm is reduced." This feedback did not necessarily require students to be convergent or divergent in their thinking. Students could implement the change as the instructor suggested or they could explore the trade-offs associated with the suggestion.

6 Discussion

6.1 Commonalities and differences across the disciplines

There were some similarities in the ways instructors from the three disciplines guided their students. Overall, feedback recommending convergent thinking was more prominent than feedback recommending divergent thinking.

Instructors assisted students in clarifying details, making decisions, and completing their work on time rather than pushing students to investigate further possibilities for alternative solutions. Their approach was to make sure all the details were covered and the appropriate justification was proposed by the students.

Structures and end goals has some key differences in the feedback sessions across the disciplines. The CH students had round table conversations with their instructors where the instructors were also designing their own performances, the ID students received feedback in one-on-one feedback sessions, and the ME students received feedback in team critiques in front of the class. The CH class was preparing for a public performance, the ID class had an external client so they were limited with the manufacturing processes and the materials available, and the ME class was preparing for a competition where only one successful team would win and where only the functional prototypes would be presented. Distinctions in feedback culture were also discussed in the work by Lande and Oplinger (2014) and Goldschmidt, Casakin, Avidan, & Ronen (2014). Additionally, the CH and ME projects required students to work from sub-assemblies to full-assemblies due to the complexity of the outcomes and design ingredients that had to work together with one another. ID projects differed since students' approaches were more holistic, creating their designs all at once. These contextual differences likely prompted variations in the type of feedback and feedback approach.

There was evidence of feedback prompting divergent thinking in both CH and ID, but not in ME. Feedback prompting divergent thinking came in the form of instructors suggesting students explore ways they could accomplish an idea or suggesting multiple options for students to consider. However, we did not find any general feedback in which instructors asked students if they had fully explored their options, whether for their overall concept or components of their ideas. They pointed to places where students needed to make decisions, but did not ask if students had given themselves enough options to decide among. Again, we cannot say this did not happen in the course as a whole, but there was no evidence of this happening during feedback sessions. The CH instructors encouraged more divergence compared to the other instructors in ME and ID. The ID instructor used convergence and divergence in combination, and the ME instructor's approach was mostly towards encouraging the students to think more convergently. This is partly due to the lack of the idea initiation data from both ID and ME dataset, where divergent thinking feedback would be expected to be observed more frequently.

6.2 *Educational and research implications*

Several implications for research and pedagogy emerged from our work that focus on the role of divergent design thinking throughout design processes and how, within the scope and timeline of design courses, instructors can facilitate students' engagement in cycles of convergence and divergence. Some potential educational implications of this research are:

Encourage divergence throughout design processes

While divergence is fundamental to early design stages, it can have an important role in mid to later phases; the amount of divergence likely changes but there are benefits to later design phase explorations. Banathy's (1996) design process model illustrated such an iterative process where the design process was described as repeated steps of divergence and convergence, and analysis and synthesis. Cardella et al. (2014) emphasized the importance of both reducing and maintaining ambiguity throughout design work, which is consistent with the necessity for convergent thinking to bring clarity to an idea and determine details as well as the necessity for divergent thinking to generate multiple options for consideration. Instructors can provide feedback that helps students see how divergence fits throughout design processes.

Ask students how they can diverge at different levels

Many disciplinary design processes are overall convergent, however, instructors can help students diverge throughout design processes at appropriate exploration levels. For example, an instructor could ask, "What are the other ways for the user to interact? (broad exploration)" or "What are five different materials you could consider here? (narrower exploration)." This integration of question-asking behavior in design education was also discussed by Cardoso, Eris, & Badke-Schaub (2014), where they introduced three question classes the design instructors used: 1) low-level questions focusing on factual information elicitation such as verification and definition, 2) deep reasoning questions focusing on analysis such as procedural approaches and goal orientation, and 3) generative design questions focusing on conceptualization such as ideation and scenario creation.

Provide feedback and develop course structures and assessments to allow for risk taking

Our analysis revealed that some of the convergent feedback directed students to minimize risk of failure in their design decisions. In our data, there were not occasions where instructors pushed students to think more divergently into "unsafe" territories, which could lead to design failures. Instructors can determine when and how in their design curricula students can have the opportunity to take risks, facilitate successful divergent thinking so that students can generate more radically innovative solutions, and allow students the opportunity to pursue these ideas in their design work, even if they are ultimately unsuccessful.

Consider the larger structure of design learning and emphasize divergent and convergent thinking in different courses or sequences

As time is often a limitation, educational programs can provide various opportunities where the focus of the courses shifts. For example, one design course could focus more on the design "front-end," holding students less accountable for a working prototype and more accountable for executing divergent and convergent strategies for defining and refining a design problem, generating and prototyping multiple ideas, and developing design requirements for a final design outcome, without actually building and assessing the final artifact. Educators can reconsider course goals to allow for cycles of divergence and convergence throughout.

Research implications include the following. (1) Researchers can explore students' actual decisions based on feedback provided and whether the feedback is applied as it was intended (divergent vs. convergent) by the instructor. Since the ultimate goal of design is to specify one artifact, students could be more likely to favor convergent activity when instructors leave decision-making to the students. Divergence is not equivalent to risk-taking nor does it lead to design failure, but divergent thinking promotes exploring uncharted idea territories, which takes time, and has risks associated with it. (2) Researchers can explore if and how risk is supported or hindered in various design course structures, and the connection of risk to divergent and convergent feedback by instructors and pathways taken by students. Finally, course goals and structures were likely connected to the feedback given, i.e., instructors provided feedback to maintain the alignment between students' design work and their goals for the course. (3) Researchers can explore divergence and convergence in successful design processes of experts.

6.3 Study limitations

The small number of feedback sessions by each discipline and the small number of instructors involved in these sessions limit our ability to generalize the disciplinary differences as it can be affected by many factors including cognitive styles of the instructors and their personal preferences; however, this analysis was not intended to generalize, but instead offer important insights about feedback use by educators across diverse design disciplines. Additionally, the data included only portions of the design processes, which limited the analysis of the outcomes. We also could not assess the quality of the design outcomes, so we could not correlate feedback types to final student deliverables.

7 Conclusions

Our analyses revealed how feedback types and structures can have commonalities and distinctions across disciplinary contexts. This exploratory study provides a means to share strategies across design disciplines. Additionally, the study highlights examples of how feedback can prompt students to think in convergent or divergent pathways. This study can help instructors to be more reflective and purposeful about the feedback they give, and how that feedback could support or hinder innovative ideation pathways. Feedback in design courses helps to shape the developmental, relational, and educational pathways of the discipline (Dannels & Martin, 2008), but instructors may not realize the level of impact they have in how they structure feedback. Our analysis revealed feedback commonly used to direct design thinking across three design disciplines. Both convergent and divergent thinking are necessary for creativity, idea development, and design success, regardless of the design discipline, thus engaging students in both types of thinking multiple times throughout their work is critical.

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