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When Tough Times Make Tough Designers: How Perplexing Experiences Shape Engineers' Knowledge and Identity*

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In this paper, we frame design as a learning process where discomfort abounds, and through the process, engineering designers iteratively reconstruct their knowledge and identity. Design and design thinking require very different kinds of cognition and behavior than engineering science. How engineers deal with their cognitive and epistemic biases while navigating sociotechnical complexities in design is a research topic that has been extensively investigated. Yet, much focus is on its know-how, leaving the actual experiences of knowledge development an underexplored domain. To reveal the internal experiences of designers, we conducted a longitudinal qualitative psychology study at a one-academic-year-long engineering design innovation course. Based on the empirical work, we theorize about a psychological phenomenon of designers stretching their mind in discomfort and confusion – perplexity. Each micro-activity of designers' reshaping of design knowledge and identity is conceptualized as a four-stage "Death Valley" of unlearning and reframing: schema incongruence, cognitive dissonance, pattern recognition, and schema resolution. We unfold how the emotional, cognitive and motivational components of the process are qualitatively different from other processes through which engineers fail to develop design knowledge in schema-incongruent situations. In the end, we discuss the potential value of inducing disturbances for learning, and draw implications for how to better construct engineering students' learning experiences.

Keywords: engineering education; engineering design; design innovation; design knowledge; identity work; educational psychology; cognitive growth

1. Introduction

This paper is concerned with the education of design innovation for postgraduate engineers. What is design innovation? Figueiredo's engineering epistemology framework positions design towards serving the society with practical skills and knowledge of engineering [1]. We adopt Figueiredo's framework and further define design by Herbert Simon's words - devise courses of action aimed at changing existing situations into preferred ones [2]. Specifically, we use the term design innovation to refer to high-level, radical design (as opposed to incremental, component design) [3] and consider the full stages from problem definition to product realization. Design innovation (1) entails complex and ill-defined problems where the ends are often confused and conflicting [4–6], (2) demands cross-cultural and cross-disciplinary collaboration and coordination [1, 7–10], and (3) requires the right problem-framing before/while arriving at a good solution [4, 5, 11, 12]. Given these characteristics, it is not hard to infer that design innovation requires very different kinds of cognition and behavior than engineering science. The former relies more heavily on abductive processing, creative thinking, and abilities to work with different cultures, ill-formed materials and complex environments; whereas the latter emphasizes deductive and analytical thinking, and excelling in controlled experiments [5, 13–16]. Students and practitioners who are used to engineering science model may find them out of place when situated in an ill-defined, real-world problem where their skills, knowledge and ways of thinking that suffice in applied science would not help much, especially in the early phase of design [11] and to the opposite, may be in the way [17, 75]. Donald Schön observed that many practitioners would confine themselves to their *narrowly technical practice* and use *junk categories* to explain away discrepant experiences [4]. Other scholars also claim that well-educated engineers tend to have difficult-to-change schemas [18, 19]. The technical interests, specialization and analytical problem-solving training may bias engineering practitioners to fixate on certain solutions rather than thinking about the real problems at hand [21–23], and result in negative impacts of products and systems [20].

How should designers deal with their implicit biases and knowledge limitations while navigating sociotechnical complexities is a well-researched topic. Related research includes the following: how critical reflection enables recognition and correction of cognitive biases and automatic thinking [4, 24–26], how certain training and practices overcomes blocks to flexible thinking and creativity [22,

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27–30], and how certain psychological tendencies (e.g., empathy, growth mindset, openness-to-experience) lead to learning behaviors in the face of complexity and uncertainty [30–31]. Despite the many theories that characterize capable learners, however, few have empirically studied the internal experiences of engineers and designers as they deal with social situations that fall out of their known categories, and how the internal experiences interact with initially disruptive social situations and influence their subsequent decision-making.

Why does it matter to learn about the subjective experiences of an engineer, who is reconstructing how to resolve a problem? This is not just to advance research of design and design cognition, but also to provide insights for better problem-based teaching and coaching. From the engineering educational perspective, unravelling the rich psychological experiences of designers would guide educators to understand their students, not just as knowledge-seekers, but also as emotional, growth-seeking individuals.

2. Theoretical Lenses

2.1 The Underexplored Internal Complexities of Recognizing and Overcoming Habitual Biases

Many have argued that effective learners take advantage of problematic situations of being *disturbed* and *confused* [24, 32], *surprised* and *puzzled* [4, 33, 34], *stuck* [35], and *disoriented* [36] to reflect on their implicit assumptions, and form new ways of thinking about the problems at hand. Bucciarelli struggled to come to a new viewpoint about a puzzling issue, during which he had feelings of *despair*, *guilt*, *cynicism* and eventually *interest* [37]. These descriptions indicate that unsettling cognitive-affective experiences are almost unavoidable in overcoming one's implicit biases. Indeed, scholars across domains have argued the necessity of cognitive difficulty and emotional disturbance. D'Mello and his colleagues argued confusion is unavoidable during complex learning tasks [38]. Mezirow theorized that for transformations to happen, one needs to self-examine *with feelings of fear, anger, guilt, or shame* [39]. Others have emphasized the role of emotional discomfort to *mobilize a creative energy to resolve discord* and come to creative discoveries [40–41]. Kegan proposed that cognitive growth emerges as a result of people's repeated attempts to *solve the unsolvable tension* between getting embedded and emerging from embeddedness [42, 43]. And from Kegan's view, cognitive growth is a complex process that involves being vulnerable to negative emotions and psychological distress and to some extent *killing off the old self*.

Change, the process of developing new beliefs, behaviors and identities, therefore could be a very vulnerable process. Consistent with these "no pain, no gain" views, we conjecture that cognitive difficulty and emotional disturbance can be an important part of shaping and reshaping engineers' knowledge and identity in the learning process of design innovation.

To our knowledge, little design research has empirically investigated the complex psychological process underlying change in engineering education. Empirical evidence exists in other domains, such as research of epistemic doubt in college students [44], confusion in the learning of scientific reasoning [38], negative emotions during mathematical learning in children [45], and discomfort in creative writing [46]. To study this psychological phenomenon in the learning of design innovation for postgraduate engineers, we use John Dewey's term *perplexity* [24] to refer to the idea of bearing unresolvable tension of expanding one's mind.

2.2 What is Perplexity?

The Latin origin of the word perplexity is *perplexus*, meaning entangled and confused. Perplexity has several conceptualizations depending on the academic context. In information theory, perplexity is a measurement of the model's fit with a sample – the more misfit, the higher perplexity [47]. In psychopathology, perplexity refers to a symptom that patients of schizophrenia would have: the loss of the usual common-sense orientation to reality and of the unquestioned sense of obviousness that normally enables a person to take for granted so many aspects of the social and practical world [48–50]. In educational philosophy, Dewey observed that a deliberate examination of the basis of one's belief starts from *a state of perplexity, hesitation, doubt . . . a situation which is ambiguous, which presents a dilemma, which proposes alternatives* [24]. In Dewey's work, the word perplexity was frequently used to refer to *a forked-road situation* in which the inquirer is disturbed and confused. Dewey also asserted perplexity to be *the starting point of challenging one's mind* and *the origin of thinking*.

Although the underlying mechanisms of perplexity in the three contexts are drastically different, they all share the connotation of misfit, instability and resistance to habitualization. The metaphoric value is clear. In psychology, Berlyne was one of the earliest psychologists to further define Dewey's use of perplexity as one kind of *conceptual conflict*, which was conceptually similar to Barlett's *gap* and Claparéde's *disturbance of equilibrium* [77]. According to Berlyne, perplexity is featured by having a number of mutually exclusive beliefs but no way of knowing for certain which is true, since

Table 1. The design process and course timeline

<table>
<tr><td>Time (by term)</td><td colspan="11">Fall Quarter</td><td colspan="3"></td><td colspan="8">Winter Quarter</td><td colspan="2"></td><td colspan="11">Spring Quarter</td></tr>
<tr><td>Time (by week)</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td><td>6</td><td>7</td><td>8</td><td>9</td><td>10</td><td>11</td><td>12</td><td>13</td><td>14</td><td>15</td><td>16</td><td>17</td><td>18</td><td>19</td><td>20</td><td>21</td><td>22</td><td>23</td><td>24</td><td>25</td><td>26</td><td>27</td><td>28</td><td>29</td><td>30</td><td>31</td><td>32</td><td>33</td><td>34</td><td>35</td></tr>
<tr><td>Project Stage Description</td><td colspan="4">Mini projects: getting to know design methodology</td><td colspan="3">Launching the design project; Needfinding and benchmarking</td><td colspan="4">Divergence: prototyping to discover the critical issues</td><td colspan="3">Between-term break</td><td colspan="3">Divergence: prototyping wild ideas</td><td colspan="2">Convergence: prototyping the overall system</td><td colspan="3">Convergence: prototyping the final product</td><td colspan="2">Visiting global partner (between-term break)</td><td colspan="9">Product realization</td><td>Exhibit</td><td>Wrap-up</td></tr>
</table>

there are factors simultaneously supporting and inhibiting each of the alternative beliefs [77]. Here, we adopt Berlyne's conceptualization and view perplexity as a psychological process of cognitive growth rather than a psychological state. We set this theoretical boundary to direct us to the phenomenon of dis-habitualization we are interested to empirically examine. Next, we describe the current study and explain how we inductively analyze the complexity of reality in the learning of design and in turn refine the theoretical abstraction of perplexity.

3. Research Method

3.1 Research Questions

Our research questions are: (1) Does perplexity exist in the learning process of design innovation? If so, what is it? (2) How is perplexity experienced? And how do designers get into perplexity and how do they get out of it? (3) How does perplexity impact designers' knowledge and identity?

3.2 Method and Setting

Qualitative psychology [51] is an ideal window to deeply understand and theorize about the underexplored phenomenon of perplexity and answer the "how" questions about perplexity. Specifically, we aim to explore the subjective experiences and meanings of the individual participants, through interpretative phenomenological analysis, and in detail the particular ways the individuals are thinking through the process [51, 52]. We selected our research setting based on the following criteria: (1) our primary focus is on graduate engineering students and engineering professionals; (2) we wanted to study intensive learning settings (e.g., courses, trainings) that demand students' experiential involvement; (3) the students' design work should reflect the nature of design innovation, as stated at the beginning of this paper. Based on these criteria, the research was formed and conducted at a one-academic-year-long graduate-level design innovation course in the Mechanical Engineering Department at a U.S. university. In this course, graduate students are formed into teams of 3 to 4 people to work on a real-world, corporate-sponsored project. Each project team also works with at least one international student team from a global university (not included in the study). The initial project prompts, ranging from healthcare to automobile, are loosely formulated by intention; the students are encouraged to generate radical innovations; and at the end, functional technological prototypes are produced. The course spans three quarters, roughly 9 months, with each quarter focusing on a slightly different theme to guide students from conception to production. Table 1 provides an overview of the course. The course also has a physical work environment and each team has a dedicated workspace for a whole academic year.

The data from which we draw were collected from December 2017 to June 2018. At the time of the study, the course had 28 students, with a small turnover in between the quarters resulting in changes of team composition for some project teams. 25 students' specializations were in engineering, such as biomechanics, engineering design, thermodynamics, and robotics, etc. The non-engineering students were pursuing master's or PhD degrees in humanities. 58% students worked in industry for 1 to 6 years before coming to the graduate school. 36% were female. The cohort has diverse cultural and national backgrounds.

3.3 Data Collection

To uncover the internal experiences of engineering learners, the primary data collection method was semi-structured interviews on a one-to-one basis, complemented by observations and written materials produced within the course. The first-round interviews were conducted from January 2018 to March 2018, with 13 participants from the course. The second-round interviews with the same 13 participants, except for one dropout, were done from May 2018 to June 2018. 3 third round interviews were done in June. 14 more interviews were done with the rest of participants between April 2018 and June 2018. All interviews lasted 1 to 1.5 hours except for one 30-minute interview with the dropout student who was uncomfortable talking about course experiences. In the end, we managed to conduct interviews with all students from 8 project teams, except for two people from two different teams, due to scheduling difficulty. Additionally, we interviewed all teaching team members and the industry-partnership manager of the course.

During the interviews, drawings of emotion maps and diagrams of internal experiences were collected. All interviews were all done by the first author. Memos were written after the interviews to track the first author's own reactions and interpretations.

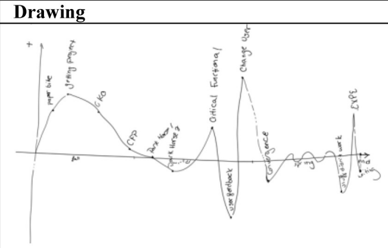
Behaviors, social interactions, environment and physical artefacts produced during the process are relevant data for deeply understanding the psychological experiences. Thus, in addition to the interviews, we attended the students' weekly review meetings whenever possible as well as their final presentations. Extensive field notes were taken during and after the observations. All the observations were unobtrusive. Additionally, course materials and students' written documents and their intermediate written reflections were acquired to inform the data analysis.

Sample materials of data collection are presented in Table 2.

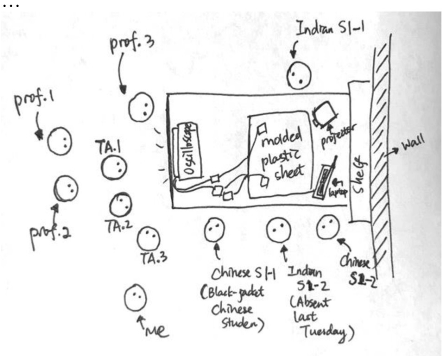
3.4 Data Analysis

The data analysis adopts an inductive analytical approach [51, 53]. The first round of data analysis involves open-coding of interview transcriptions, sketches and diagrams that occurred during the interviews, using Nvivo 12, a qualitative data analysis software, to tag and categorize the design activities and subjective experiences. Out of the

Table 2. Examples of how data was collected

Interview example		
06132018; Noon; Café X (location of interview)		
Person	**Transcript**	**Drawing**
Researcher	Can you give an example?	
P82	… when we talk to them, we were like: 'look this, you don't put wheelchair in the car, you have so much more space, and you can just… your independence is much more manageable, you don't have to disassemble your wheelchair all the time'… Their wheelchair is like their legs, as they put it. One thing they told us is really crazy…	
Researcher	It's very vivid when you say that nobody would put their legs out of the car… (interrupted by P82)	
P82	Yeah, it's so obvious, yet you overlook it. and then, you are like, duh, like that. unfortunately that's the best thing I can say…	

Memo example
… 11112018 I've just re-read the interview with P82 and realize she liked talking in a third person perspective. She talked about herself and the team using "you" instead of "I" or "we" a lot. I think that partially contributed to revealing very few emotional incidents during the interview.

Observation example	
Observations: Actions, language used, interactions, etc.	**Interpretative comments:** Reactions from the observations.
05222018; 1pm/5pm … ~2:17pm to ~2:26pm: … Chinese S1-1: "Actually for this one, we, I think we are getting, like, very clean signal." Prof.2, smiling: "Yea. You see, you are contradicting yourself now." I suddenly see that Prof.1 has also lifted his eyes from his paper, moved his chair closer to the table, and is now paying attention to the conversation, leaning forward, smiling, with "sparkling" eyes looking at Chinese S1-1. Chinese S1-1, looking confused: "Hmm?" Prof.2: "So you are saying that…" Prof.1 interrupts prof.2: "You are saying that you have too much noise and you are getting a clean signal." Chinese S1-1: "I mean from…" …  **Fig. 2.** The initial layout of the people attending team 1's small group meeting.	… This episode of interaction is quite intense in the outsider's eyes of mine. The conversational turn-taking between the students, prof.1 and prof.2 is very fast… there is a miscommunication between the students and the teaching team. From my perception, Chinese S1-1 (and also Chinese S1-2 and Indian S1-2, who attempted to make a point, but didn't get much chance) was very curious to resolve the confusion. He looked serious (and worried?) throughout the time, arms folded tightly. He sometimes bit his lips when he listened. (Note: the labeling was synchronized with interview data afterwards)

first round of open coding, we discovered that although they took the same course and worked mostly under the same roof, the engineers' experiences were drastically different from team to team and from person to person. We were also surprised at the wide range of discrepant experiences the participants had, including looking for the design problem through fieldwork, prototyping by "sacrificing" quality technical work, everyday decision-making in the wild, high interdependence with teammates, and lack of a right answer from the teaching team and so on. In the second round of coding, we coded all the reported disruptive, schema-incongruent problematic situations, as well as the ways that the participants responded in the situations. This was partly inductively derived and partly built on literature of design research and learning sciences [54, 55]. With that, in the third round, we searched for incidences of perplexity, and looked for patterns and contradictories. The analysis resulted in a theoretical framework, building upon a few prior works [56, 57], which we present in the next section. The analysis took six months in total, and was led by the first author, with extensive work sessions with the second author and their research group.

In terms of research qualification, the first author took one qualitative analysis course in School of Education, one qualitative research seminar for PhD students in School of Engineering, as well as a PhD seminar course that involved a lot of discussions on qualitative inquiry. The first author has practiced qualitative research methods since 2016.

4. Findings

To contextualize the description and discussion of our findings, we give a synthesized sketch of the course experience. Students accessed the course's physical space with their student ID cards. The open workspace has a big workbench with prototyping machines and cabinets of tools located at one wall, and 9 desk-chair sets lined by the other three walls. Right in the beginning, the professors of the course set expectations that "*don't expect answers from us, we might in turn offer you more questions to think about*". Before the main corporate-sponsored projects, a few mini-projects were introduced to kick off the course and familiarize the students with the design process, and the rituals, norms and ways of interaction in the design community. After the highly-compressed two weeks, the project teams were formed by the coaches, based on individual preferences of project topics and teammates. Each team got a workstation. Design briefs were delivered by the corporate liaisons. Like most others, the example here set little constraints:

> Trends such as automation, electrification and digitization are changing the construction industry. The conditions for our industry are also changing, for instance cities will ban diesel from 2025 on construction project . . . Although automation might remove some jobs, the majority will not be erased, but potentially redefined through human-robot collaboration . . . Now, we want You to help further define the way forward . . . Create a new, tangible solution that would make a big difference for workers on future job sites – and possibly some pieces of that solution could be helpful even today.

The course had one formal lecture each week, topics covering problem scoping, benchmarking, design requirements, prototyping, teamwork, foresight thinking, bias in design, storytelling, manufacturing plan, business model, and so on. All the course resources were posted online in the course's internal website as well. In addition, every week, a 45-minute-long design review meeting was held for each team, where three professors and three coaches came in to learn about the team's project progress and give them customized guidance.

Almost every engineer talked about how overwhelmed they were by the broad project prompt for the first few weeks. Despite the structured design process, the engineers were not sure how to decompose the problem and narrow the scope. "*. . . nobody did it before. We have to discover the trace by ourselves . . . sometimes it made me feel anxious – you feel you have a lot of things to do, but at the same time, you don't know what to do*", as one engineer P13 said. Some engineers shared skepticism about what they were taught. P11 was one of them – "*I was skeptical about a lot of things, because I'd be like - this doesn't help much . . . when we worked towards an assignment, I would often think 'this won't work. . . why would we do this?' Even with the stuff like creating a persona, critical functional prototype, and . . . everything . . .*"

All the engineers had educational and project experiences before the class which shaped clear, if not rooted, ideas of engineering and design. Now when the course under study introduces concepts and practices that contradict theirs, they resisted. The discomfort-abound journey went on. The engineers were disoriented by the new ideas of human-centered design (e.g., P52: "*It took me a really long time and I'm still not totally understanding it . . .*"), rapid prototyping (e.g., P81: "*Every week I'm frustrated almost, because we don't have enough [working prototypes to show] . . . I want to do something more and finish more . . .*"), teamwork (e.g., P81: "*I had plenty of group projects, but it was easy. I'll take this section and I'll do this work, and you do this.*

[But] this project can't be divided like that at all"; P43: *"I feel now the focus is much more on how to work with a certain team. I don't think any more that in this constellation we will be able to do something really innovative . . . So, I just have no idea what we should do . . . it feels a little bit like just staggering in the dark*") and creativity (P51: "*We weren't comfortable with . . . ideating and coming up with creative solutions . . . Although . . . we were comfortable with expressing ideas. I mean it wasn't that we felt any less creative. But because we actually have to build it. And I'm technical here! We question whether we could actually get this done and [whether] we were good enough to get this done"*).

By the end of Winter Quarter, teams needed to finalize their design solutions and get ready for higher-fidelity prototyping and production. Half of the teams were not able to finalize project direction until a few weeks into Spring Quarter, due to various reasons of team conflict and design concept quality. The last few weeks were featured by sleepless nights of tinkering, synthesizing, and presentation preparation. According to one of the professors, the course ended with high-quality product outcomes.

4.1 Categories of Problematic Situations and Cognitive Approaches

We identified 125 problematic situations along the design innovation projects as perceived and reported by the participants. These were disruptive, schema-incongruent situations, and examples can be found in the first column of Table 5. A summary of the problematic situations can be found in Table 3. The 18 technical development-related problematic situations happened mostly in the final term where product realization is demanded, whereas the 76 design cognition-associated problematic situations occurred mostly in the first two quarters. In comparison, the 87 problematic situations of social interaction spread across the three quarters. Some of the situations reflect their confined practice when participants were surprised to find the project undividable amongst the team, or were puzzled at coaches disagreeing with each other in design reviews. Some were distinctive to design thinking, such as learning to find user needs by staying in the field for a few hours, entering the design review with a failed prototype, and finding the problem to solve rather than providing a solution to a given problem. And as indicated in Table 3 and predicted by theories in Introduction, most of the problems reflect the dichotomy between engineering science and design innovation practice.

After analyzing how individuals experienced and dealt with problematic situations, three types of cognitive approaches become apparent: habitual thinking, compliant thinking, and deliberate thinking. Habitual thinking represents assimilation of new information into the current conception, and is often characterized by defensive behavior [59]. For instance, in several cases, participants expressed dissatisfaction with their project directions, and they readily attributed their problems to the lack of systematic course structure, lack of good coaching or problematic teamwork, and did not show any intention to improve the situation from their ends. Compliant thinking is often characterized by adopting a given frame under power or shared identification [54]. This was exemplified in some designers who followed course instructions without any indication of reflection. Deliberate thinking is characterized by effortful slow thinking and intentional action [4, 55, 60]. Several participants showed deliberate practices of dealing with, for instance, anxiety, lack of candid team communication, and doubts of new concepts. A mix of these cognitive approaches are found in the same individuals dealing with the same problematic situations and sometimes at the same time.

Intriguingly, although a majority of the perceived problematic situations were approached with only habitual thinking and/or compliance (80 out of 125), very few cases were resolved without habitual thinking. The positive cases all entail cognitive dissonance, where the participants had to deal with the tension between habitual mind and decentralizing mind, consciously or not. There are 45

Table 3. Counting [58] of perceived problematic situations

Category	Count of Problematic Situations
Design as Cognitive Activity (e.g., need-driven vs. idea-driven, letting go vs. persistence, rapid prototyping, and decision-making, etc.)	76
Design as Social Activity (e.g., interaction with user, local teamwork, global teamwork, coaching/teaching, project sponsorship, etc.)	87
Design as Technical Activity	18
Total*	125

* Including overlaps caused by not-mutually exclusive categorization

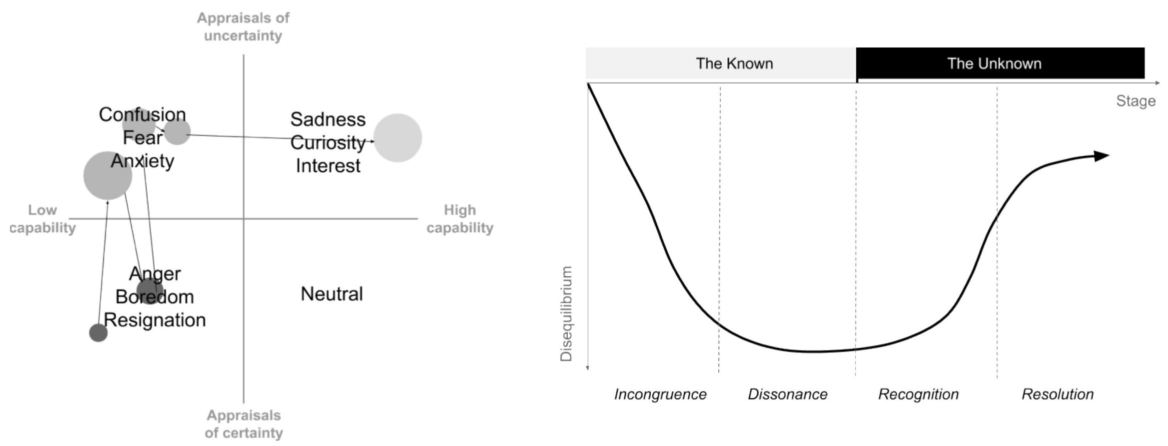
Table 4. Counting of experiences identified as perplexity by types of problematic situations (top) and learning outcomes (bottom)

Category of Perplexing Experiences (by schema-incongruent problematic situation)		
Design as Cognitive Activity	Ambiguous project direction / problem-framing	2
	Functional prototype failure	2
Design as Social Activity	Interaction with user	1
	Team interaction	4
	Interaction with coaches	5
Design as Technical Activity	Technical sophistication	2
Total		**16**

Situated Learning Outcomes of the Perplexing Experiences	
Design judgment	4
Dealing with ambiguity and complexity	3
Dealing with incongruent perspectives	4
Mobilizing resources and network	2
Design process	2
Recognizing hidden design biases	2
Prototyping to learn, not to show	5
Human-centeredness	2
Total*	**24**

* Multiple learning outcomes were found for each perplexing experience.

cases of such. Within the 45 cases, 16 are identified of including perplexity, where the dissonance was positively resolved. 1 case was unidentifiable for lack of enough information, and the other 28 cases that entailed unresolved cognitive dissonance do not seem to result in a change of behavior or a leap in learning. Because of space limitation and the paper's focus, we will focus on the cases of perplexity. Table 4 categorizes the 16 cases by situation and outcome. The data analysis also results in a framework of perplexity, represented in two schematic forms, as shown in Fig. 1.



(a) (b)

Fig. 1. The cognitive and emotional process of dealing with discrepant experiences through perplexity in a 2 by 2 framework (a), defined by Low/High capability of comprehending the situation at hand × Appraisals of situation with uncertainty/certainty. (b) gives the conceptual Death Valley of reframing one's habitual thinking of a problematic situation through the process of schema incongruence (surprise), cognitive dissonance (confusion), pattern recognition (curiosity) and schema resolution (relief). Going from cognitive dissonance to pattern recognition allows one to step out of the known world into the unknown. (a) captures the middle two stages of this process - going between bottom-left and top-left quadrants (cognitive dissonance) and going from top-left quadrant to top-right quadrant (pattern recognition). In this study, for 80 of the 125 problematic situations, participants' experiences stayed in the bottom-left quadrant; 28 cases had cognitive dissonance (left two quadrants); and only 16 cases crossed the Death Valley (from bottom-left to top-right quadrant). Table 5 gives a few examples of going between the different cognitive-affective states.

4.2 Perplexity: The Journey from Surprise to Confusion to Curiosity

What is perplexity? Building upon prior work, we theorize from the current study that perplexity is triggered by disruptive, schema-incongruent situations (unfamiliar external stimuli), as well as the internal stimuli to preserve the conflict aroused by incongruity, the latter of which is reliant on individuals' motivational process and situated mindset. Upon schema incongruence, one experiences anxiety resulted from the dissonant beliefs of self-confirmation (e.g., anger) and invalidation (e.g., fear). Confusion is aroused as the individual tries to resolve the dissonance, and eventually leads to interest and curiosity as he/she starts to form a novel pattern and a deeper level of understanding of the situation at hand. The process ends with schema resolution. The process of perplexity is illustrated in Fig. 2 (abstract) and Table 5 (concrete). In the current study, the instances of perplexity are diverse in its content, yet distinctively associated with the particular social and physical contexts of engineering and design.

What does perplexity look like? From the emotion maps, most of the participants perceived the experience as a big emotional drop, while some participants visualized it as a line with abrupt alternating turns, as Table 5 shows. Fig. 2 (a) and Table 5, with great simplification, summarizes the three cognitive-affective states individuals would go through and how situated, tacit design knowledge is internalized. The subjective experiences also reveal that identity re-establishment is part of the process of deriving new understandings of design and the self.

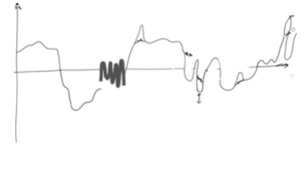
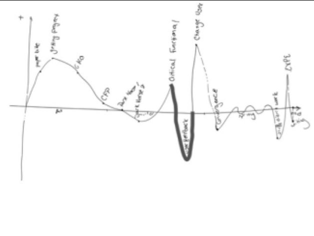
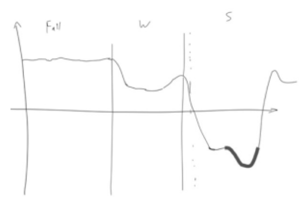
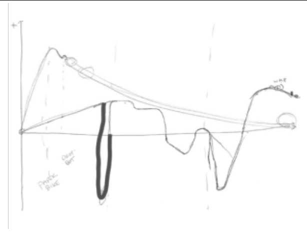
Through the framework of perplexity, we can see that a perplexing experience can be differentiated from other difficult, confusing experiences. To illustrate with Fig. 2 (a), the internal experiences of some other forms of difficulties may stay within the bottom-left quadrant, or within the two left quadrants without crossing the line from confusion to curiosity.

To further analyze the differences, consider the following experience from P12. P12 had "*a time in [Winter Quarter] when whatever idea we thought could work was not a good idea at any point of time*". Being in the "*demotivated team*", P12 said, "*I don't know if there's a word for a lot of frustration. I was tired. I was angry. I had so many questions about the whole process as well. I mean why do we do such a project first of all? I do not know how to go about it. But at least tell me if there is a rule book for this? Can I go back to a rule book and see in such a case [how] you should do this?...*". Though the experience was unique to P12, comments about feeling frustrated and not knowing the project direction in the middle of Winter were not uncommon. We can map such a defensive state of mind to the bottom-left quadrant of Fig. 2 (a). Some participants chose to move forward with a passive attitude, and attributed the problem to others (the course, the teammates, or the sponsor). For instance, P13 also had a pretty negative experience – feeling "*uncomfortable*" and "*breathless*" about not knowing the project direction. Following the curriculum did not help. And P13 reasoned that "*there lacked step-by-step procedures [in the course], so that the team did not have the confidence in developing the product, and [we] ended up in a mess*". In contrast, P12 started rethinking about previous, taken-for-granted engineering practices, and wondered what it really meant by navigating ambiguity in design, because "*what we normally do in engineering – break up big problems into smaller problems – doesn't apply in such scenarios*". As one can see, compliance does not guarantee learning. The start of learning comes from a decentralization of one's habitual mind, to see the uncertainty and complexity of the situation at hand. The recognition that the analytical approach of engineering might not work in such scenarios elicited confusion and anxiety ("*I don't know why it's difficult*"), and what P12 experienced here can be mapped to the top-left quadrant of Fig. 2 (a).

Intriguingly, we observe over and over again how inarticulate participants became as soon as they started talking about experiences of such, whether "*it just happened yesterday*" (in one of P23's cases) or it was from two months ago. They would also become self-contradictory. For instance, when talking about one prototyping experience, P81 went back and forth between "*frustrated*" about not able to "*fully realize things*" functionally and "*it's good that we pivoted*". It also appears that participants were not aware of their process of conceptual change, at least before they verbally reflected on these experiences with the researcher. Behaviorally, some participants paused and appeared surprised as if they discovered something for themselves. We thus conjecture that the process from the defensive state of mind to the decentralizing mind is nonlinear, as visualized in Fig. 2. However, we do lack objective measures about such internal dissonances.

The most puzzling part of the psychological process is how to cross the line between confusion and curiosity. Building upon related prior works, it is suggested that prevention-focused emotions that activate individuals (e.g., fear, with unfulfilled prevention goals) may underlie the processes of conflict mindset/paradoxical thinking [61–64], negative capability/reflective inaction [65], and negative creativity [66–67]. With appraisals of uncertainty (e.g., the mindset of embracing conflicts/disorientation), the

Table 5 Examples of learning through perplexity

Schema Incongruence	■ Low capability × Appraisals of Certainty*	■ Low capability × Appraisals of Uncertainty*	■ High capability × Appraisals of Uncertainty*	Schema Resolution	Perceived emotional response** (Thickened line; texts are not meant to be readable)
In developing a robot, P22 got questioned by a non-engineering team member about the necessity of certain functionalities of the robot	"I feel indignant if something definitely in my domain, where there's a mechanical issue or a mechanical design decision, and I'd say it should be done a certain way. . . And then having someone who doesn't have that background disagree can be frustrating because it's like – well, you should respect that."	"It's like this weird tension where it's like... (the informant didn't finish the sentence), I also catch myself – 'No, I should be open-minded, I should really think about it . . .' So, I try to catch myself before I fall into those traps of being imposing my knowledge to people."	"the ways people are trained to think are very different. . . Engineers always want to give more functionality to products and you never think about why, or how does that actually play into the final product. . . I never looked at it that way, since I've never thought to myself maybe I shouldn't give functionality to something in that regard. . ."	Became conscious about the self's engineering mindset and understanding product design holistically	(Not available)
P23 presented the project progress to a new team member from non-engineering background, but was seriously questioned	". . . she (the new member) is like – 'this is not going anywhere', and my team's coach is like – 'No. Not a good idea.' This is for someone who's been in the team since in Fall, [and] this was the direction that we thought would work. . . So that's really, very uncomfortable. I spent a quarter on the idea. Now, the student from Education just tell me it's not going to work!"	"We were honestly lost, because I was trying to explain to the new team members what we did [in Fall] . . . I was just thinking why am I doing this? Why did I do all those prototypes? I couldn't see. . . Why did I even try to do these [prototypes]? I was just wasting time."	"Before, I thought design thinking concept was stupid. . . For the whole design process [in Fall], I went through it, but I didn't get it, because I didn't understand what I was supposed to get from it. . . Going through the whole process again and again gets me more aware of why you do each step."	Came to understand the value of the design process rather than blindly complying with it	
P82: ". . .We've already spent so much time to build this. I've got it to work. This is great. . . [Then,] we get user feedback, we are like 'BANG'	"We were so proud. . . we were like – 'look this, you don't put wheelchair in the car, you've so much more space, and you can just. . . your independence is much more manageable, you don't have to disassemble your wheelchair all the time.'. . . they were like – 'I would never use this'. I was like – 'What? Why? This is so... This is great! This is what you want'. They are like – 'No'."	"(Self-doubted that) what we just did was all [missed words] like a complete disaster. . . we spent a whole Winter and built something that nobody wanted. . ."	"Their wheelchair is like their legs, as they put it. One thing they told us is really crazy – 'Do you put your legs outside the car when you are driving?' Absolutely not. I would never do that, if somebody hit my legs. . . what can I do? . . . So that's exactly, we miss that key thing. After the fact is like, oh, yeah, duh. . . It's so obvious, yet you overlook it. And then, you are like duh, like that. Unfortunately, that's the best thing I can say, is duh, why did we not think of that... So, we give more meaning to the wheelchair at that point. . ."	Gained deeper understanding of human-centered design (design to fulfill the meaning for the users instead of simply building something usable)	
"we thought it wouldn't be so hard" – An "easy" technical implementation turned out to be much more difficult for P81	"for the last three weeks, I was working on the electronics. It shouldn't have taken a few weeks and I should've been finished it quickly, but it kept having problems. I was pessimistic about the project for this. . . I definitely got annoyed a few times, because I think people were not as concerned as I was, and weren't working as hard as they should be . . ."	"I didn't think it was going to work. I was really scared. . . It made me question what I was doing. It definitely made me question whether I was good at what I was doing. It was very stressful . . . Maybe made me upset about my other work and everything else. . . I was also extra concerned, because I would be a [coach] next year... If our project is a complete failure, how can I come back next year and teach the class?"	". . . probably most importantly [is] learning to separate myself from the success of the project. I mean that's a personal change. . . In the past, I would probably be super upset at this point. . . I think just because I had a problem but not a problem I could solve, that forced me to move on. . . I just get over and say it's ok if something doesn't go right. . . I'd not be in a good place right now if I hadn't been able to have myself separate from the project" (Eventually, the informant successfully built the system)	Became comfortable with unmanageable project complexity	
"We put in a lot of work and made really strong [and] pretty cool functional prototype" – P52 got unexpected "blockbuster" feedback during one of the early design reviews	"the teaching team squashed us down – 'Oh yeah, you built the thing. That's cool. But is this really a critical functional prototype? I don't understand. . ." [my teammate] and I were just really depressed and sad for two days. It's like all this work means nothing to them, and do I even want to keep doing this? . . . we had a really low opinion of X (one of the coaches), if I speak honestly. [One teammate] and I were very frustrated about X – 'Oh man, oh, this is very terrible.'"	"I don't know if we learn to trust him (X) more? Or I think we realized that [another coach] wasn't there to be nice and give us good feedback, so we had to learn to co-exist with X. . . I mean we put so much effort into it (the prototype), thinking they would praise us for the technical solution that we've done such a good job or something, but actually X pinpointed that we hadn't really leant a lot from it, relative to the amount of time we put."	"It's really about us accepting X's feedback and learning to take in criticism better, and not take it personally. . . I think we were able to take in [the feedback] and not just kind of wallow in self-pity. . . but it took us a couple weeks to process it. [the Winter break] really gave us time to think over – [given that] this is our goal, is this realistic? What have we done to make this happen? What are we gonna do next? What have we learned? . . . Once we realize X is trying to help us by pointing out the weak points, we were very in touch with his feedback. . .	Learned how to drive the project forward by maximizing learning experience with teaching team's support rather than seeking approval for technical ability	

* Refer to Fig. 2. ** The emotion maps were drawn in the final round of interviews, where y axis represents emotional valence and x axis represents project timeline.

activating, prevention-focused emotions would increase the breadth of attention, accessibility of broader knowledge, and unconstrained mental search for novel information. The combination of appraisals of uncertainty and prevention-focused emotions may have played a key role for the perplexed minds to not just ask, but also to chew on and find out about what otherwise seems obvious and self-evident: why it was difficult to apply what normally worked in engineering in the ambiguous decision-making situation (P12), why they even tried to do all those prototypes without understanding the purpose behind each (P23), why they've built something that "*nobody wanted*" (P82), and why they had this "*fear*" to think about if they were wrong (P22), and so on. Our data suggests that individuals' motivational process and the situated mindset may have explained the drastically different lived experiences within the same well-performing or ill-performing teams. In Robert Pirsig's words, to resolve stuckness, "he has to care!" [35]. In addition, the learner has to keep the mind open, and defer their judgement about any cognitive conflicts and emotional disturbances that are elicited by the problematic situation at hand. The theoretical framework of perplexity encapsulates such rich emotional and cognitive experiences.

4.3 "I'm Still Not Totally Understanding It" – The Situated, Tacit Design Knowledge

The knowledge gained from each individual's specific experiences of perplexity was always tacit in nature. For instance, P82 internalized the idea of user-centered design and rapid prototyping. Her knowledge, on the other hand, is specific to her own experiences, as she put it, her *"own problem"*, the kind of project she was in, her team, and her team's ways of interaction with other stakeholders as well as the cultural ideas of the course. Such knowledge is contextual and non-verbalizable. In other words, the knowledge is not objective, descriptive knowledge (e.g., certain material's physical property), and is not simply prescriptive process knowledge either, but subjectively constructed know-how in situ [3, 68]. In P82's case, it was about how to go about a design project in the early phase in order to maximize learning. More examples are presented in Table 5, in Schema Resolution column. Consistent with the literature, design at the higher level of hierarchy calls for a great deal of tacit knowledge related to design feeling and judgment [3, 69].

Given the nature of such design knowledge, it is difficult to learn, even through project-based learning. For instance, although the ideas of human-centered design and problem-framing were reinforced again and again throughout the project-based course, six months into the project, P52 still commented that "*It took me a really long time and I'm still not totally understanding it, but it took me really long time to understand this concept of needfinding and what is a need and what is a user, and why should they drive the solution . . .*". It is easy to know the design knowledge of conducting needfinding, but hard to internalize it. And the process of perplexity enables the internalization – a deeper spiral learning of the situated, tacit knowledge.

4.4 "Am I Good?" – Sadder, but Wiser

Learning happens the hard way through perplexity. The state of mind which we characterize as confusion, for the sake of simplicity, is found to entail despair and fear associated with identity threat. This is when an individual begins to be conscious of their incompetency as they chew on their confusion and discomfort – a realization of incompetency/low capability (i.e., "I thought I knew, but I really don't"). Importantly, these are capabilities closely associated to who they are as an engineer – why and how to build prototypes, how to address problems, how to work with others in design, and how to deal with technical challenges. Therefore, a big part of learning is about reestablishing engineering identity [78]. As P81 put it, "*this was the turning point for me personally*".

One associated pattern that emerges from the data analysis is that most participants did not perceive themselves to be happy again as they recover from the disequilibrium. Unlike Cremin's study where writers found it retrospectively satisfying, both artistically and personally, after experiencing the discomfort of bearing uncertainty during creative wiring [46], it appears in our study that the negative experiences in most cases of perplexity lingered. In other words, the participants still had a negative feeling about their negative experiences, even though they did realize it was a good learning experience after all. This is reflected in their word choice and how they articulated their stories – e.g., "*it really forced me to think of a different way*" (P51).

Why? We conjecture that it is primarily because most of the perplexities were strongly associated to identity reestablishment. One's attitude towards negative emotional experiences is socioculturally constructed [42, 70], and in our context, reflects certain values of engineering, design and professional work, such as "Engineering is rational", and "I shouldn't be out of control". The deeply-rooted cultural ideas of engineering shape engineers' professional identity and definitely make it difficult to embrace new cultural ideas and reshape engineering identity [75]. Understanding these is important for engineering educators when they introduce novel concepts and educational approaches.

5. Discussion

5.1 When Learning is meant to happen, but does not happen

As the study shows so far, frustrations, skepticisms, surprises, and confusions can be an important disequilibrium to go through in order to really shake engineers' minds about how and why to make things and design products. Intriguingly, although disturbance open up new opportunities to learn, it is also a double-edged sword, for that it may become a "Death Valley", as shown in Fig. 2 (b), if an engineer is stuck in distress or refuses to deal with the disequilibrium. In dealing with problematic situations, participants in our study did not cross the "Death Valley" most of the time – 80 out of 125. In the analysis of the 125 cases, the prevalence of habitual and compliant ways of dealing with discrepant experiences and the rich emotionally disturbing data points has made us rethink design innovation education both in the course under study and more broadly.

5.2 Implications for Engineering Design Education

The current study suggests:

1. Few cases happened without habitual, defensive thinking or compliance. Being angry, indignant, frustrated can be a normal part of handling discrepant stimuli, of crossing the "Death Valley" of reframing.
2. The process involves vulnerable moments where engineers try to redefine who they are and why they do what they do. As educators, we not only need to recognize that students' strong reaction is normal, but also need to be mindful about how to guide them to go about the vulnerable identity work.
3. The engineers who were able to cross the line in certain situations were not able to do so in many other cases. Therefore, what matters is not only the broad psychological tendencies or goal orientations but also their situated mindset in the micro-settings of sociophysical interactions in design. This opens up a lot of coaching intervention opportunities in the moment in context.

Unlike many project-based learning courses where real-world projects are greatly simplified to be manageable and "learnable", the course under study introduced a lot of real-world *messes* [4], which in part introduced many problems its students had. Do engineers learn better in a smoother learning journey? We doubt so. The shift of thinking does not happen through memorization of materials or acquiring a few liberating design methods [76]. As we have shown above in section 4.3, active engagement in project-based learning is not sufficient, if students choose not to engage with disturbing problematic situations.

Yet, although educators talk a lot about embracing failure in classrooms, how well do we enable students to embrace negativities, dissonances, and unconfidence in the learning settings? How well do we recognize it when students have these issues? How well do we support our students to deal with them rather than simply getting rid of them?

For engineering educators, understanding the value of getting into trouble in learning design and its underlying mechanisms is critical to address the remaining question of how to incorporate this insight to better teach and coach design innovation for postgraduate engineers.

6. Limitations and Future Work

The research method has certain limitations. Interviews are limited in retrieving accurate, in-the-moment internal experiences. To deal with the issue, we tried to maximize the study validity by triangulation and longitudinal data collection. For instance, we compared interview findings with situated behaviors, as well as interviews of the same participant from different times. The number of perplexing experiences from this study is not an objective measure of all the perplexities that happened to the participants. Instead, the 16 perplexing experiences and the other 109 reported difficult experiences were only those that surfaced from the study. Finally, generalizability to populations is also beyond the scope of the current work. Future research can be done to address the limitations.

The study has opened up more questions about perplexity. For instance, given the small number of perplexities compared with other types of experiences upon schema incongruence, we wonder whether perplexity is rare or just difficult to capture with the current research method. We started addressing the issue by interviewing several design professionals who have gone through similar engineering and design education. They not only identified with this psychological phenomenon, but also shared intriguing stories of their own. We thus conjecture perplexity is not rare, and it occurs not only to the novice but also to expert designers who would need to continue improving towards mastery [71]. Future research should study perplexity in other populations of design and engineering.

The tacit and situated nature of design activity and knowledge makes engineers' cognition and emotion elusive to be fully understood [72, 73]. An important step to advance our understanding of how schema incongruence shapes learning is to collect more accurate and granular data about the social, physical and interpretative parameters that channeled the participants' cognitive and behavioral choices [74] as they deal with problematic situations in design. This would also help explain why and how the same individual behaves habitually in certain situations but is channeled to think more dialectically in other situations, as we found from the current study. Other future directions include addressing the generalizability issue, and exploring how to operationalize and refine the theoretical frameworks derived from the study in other forms such as controlled experiments and quantifiable survey measures.

7. Conclusion

How engineers deal with their own biases and knowledge limitations is mostly hidden in the uncelebrated practices of design work. The learning of design innovation requires us to see deeply-rooted ideas and practices of engineering, as well as to deal with the tension between disparate mental models, which can involve perplexities and identity work for postgraduate engineers. Such learning process can be emotionally turbulent and full of difficulties. To understand this phenomenon and derive theories to better guide educational practice, the current research has investigated engineers' psychological processes as they deal with difficult, schema-incongruent situations in design. Our work shows that there is a potential value of disturbance in learning tacit, situated design knowledge and re-establishing professional identity. We have discovered that the mechanism through which such learning occurs can be characterized as a four-stage psychological process: schema incongruence (surprise), cognitive dissonance (confusion), pattern recognition (curiosity) and schema resolution (relief). Building upon Dewey's inquiry into thinking, we use his term *perplexity* to represent this unsettling process of learning. In addition, we examined its cognitive, emotional and motivational components at each stage of the process in comparison to other lack-of-learning psychological processes. Our research is built upon and contributes to the literature of developmental psychology, educational psychology, and engineering education. We hope the current work inspires engineering design educators to employ the lens of perplexity to reexamine their engineering cultures, design innovation practices, and students' learning experiences.

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