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Dealing with Ambiguity: Leveraging Different Types of Expertise to Guide Design Questioning*

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Questioning is important for understanding the fundamental design process. Design itself can be viewed as a question driven process. When we consider question-asking behavior as a means to manage convergent and divergent modes of thinking by decreasing or increasing ambiguity, expert designers draw either from domain knowledge and/or their situational transactions. In engineering education, it is important for engineering students to acquire an epistemological inquiry process as well as learn how to operate in the concept domain. In order to develop an understanding of question-asking behavior in design and of how we can include both divergent and convergent thinking in design, we wanted to explore how design experts use their expertise to solve a complex problem through questioning. To do this, we took an inductive approach and examined the question-asking behavior of 6 expert designers during a 3-hour verbal protocol analysis where they were asked to design a playground. Three were domain experts (playground designers) and three were non-domain experts (engineering designers). Through our work, we learned that all the design experts in our sample ask questions and that their questions occur throughout their design process. Questions that decrease ambiguity were prevalent for all participants in our sample, particularly in the beginning phases of their design process. In instances where the design experts increased ambiguity through questioning, the questions were distributed among the questions that decrease ambiguity. The questions posed by the engineering design experts were predominantly based on technical aspects whereas the playground design experts posed questions related to community aspects in order to understand the social and physical situation. From our work, we conclude that the range of variability in the kinds of questions posed depends on the kind of constraint the design experts choose to focus on, their experience and the kinds of knowledge used. In this study, the questions posed helped the design experts understand and push problem boundaries as they engage in both convergent and divergent design behaviors. This has implications for teaching question-asking techniques to help students with their design process and outcomes.

Keywords: questioning; domain expertise; design processes; convergent and divergent thinking; design cognition

1. Background

The objective of this research is to understand the question-asking behavior of 6 expert designers during a 3-hour verbal protocol analysis where they were asked to design a playground. Of the 6 individuals, 3 were domain experts (playground designers) and 3 were non-domain experts (engineering designers). These individuals' question-asking behavior is worth noting because, as a part of the study protocol, their designs received high quality scores, as determined by an experimental study evaluation. Identifying high quality question-asking behavior might help us teach question-asking techniques to design students to improve their design process and design outcomes. This paper begins with a brief discussion of the literature on expertise in general, design expertise specifically, and question-asking in engineering design. We then discuss how the research team used verbal protocol analysis of the transcripts of three domain experts and three non-domain experts to understand their question-asking techniques. The findings give an overview of the notable question-asking behavior of our participants, the functions of different types of questions asked, and specifically, the use of questions that increased ambiguity. Finally, the discussion shares the implications for teaching question-asking techniques to help students with their design process and outcomes.

1.1 Domain Expertise

Fields such as psychology, design, and engineering have tried to understand the differences between experts and novice practitioners. According to Feltovich, Prietula and Ericsson, domain expertise is characterized by the creation of large meaningful patterns, whether this be in chess moves for expert chess players or design solutions for a playground designer. Experts structure their knowledge in more complex and appropriate ways than novices, allowing them to reason in a deeper, more functional manner [1]. Because of this, experts can generate the proper actions necessary to reach solutions using rapid recognition-based problem solving [1]. With design expertise specifically, designers have a set of

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previous solutions in mind before solving similar problems. Good designers can cope with uncertainty and in fact, impose order by instantiating a solution concept. Ullman, Dietterich and Stauffer state that "only some constraints are given in a design problem, other constraints are 'introduced' by the designer from domain knowledge and others are derived by the designer during the exploration of particular solution concepts" [2]. During their design process, experts co-design problem-solution spaces, with the goal of finding a problem-solution pair that generates the best design solution [3]. Expert designers' research strategy includes: having a quasi-standard set of questions, actively seeking or creating patterns within data, and having a storage of knowledge of solution precedents from previous experience or domain knowledge [4]. Overall, we see that experts take a unique approach to creating design solutions. In this paper, we focus on the question-asking behavior of these six experts.

1.2 Questioning in Engineering Design

Leifer and Steinert [5] draw on Eris's research [6, 7] noting that questioning is important for understanding the fundamental design process and that design can be viewed as a question driven process. In addition, questions may act as a design performance metric. In *Effective Inquiry for Innovative Engineering Design*, Eris [6] highlights the importance of question-asking to the conventional design process [6]. Eris' initial goal was to understand the question-decision duality that drives the design process; that is, designers need to ask questions in order to ideate and gather information that allows them to make decisions, but he realized that in order to approach this problem, he needed to create a question taxonomy to classify the types of inquiry he was observing. In order to do this, he observed groups of graduate students tasked with the creation of a device that measures body curves, recording their design sessions and using the data to develop a question categorization schema.

Some existing taxonomies guided the development of this schema, but none of these had been applied to the design inquiry context before. Notably, Eris documented the existence of Generative Design Questions (GDQ), or questions that serve to preserve or increase ambiguity. These are questions that do not have a single answer with a truth value; instead, they assist the asker in guiding a "divergent thinking process", where designers are ideating many different solutions to a known problem. Eris also describes "low-level questions", which he makes a point to note are not "low value questions," they are simply the products of the information-gathering process that must take place before "higher-level" questions such as Generative Design Questions (GDQ) or Deep Reasoning Questions (DRQ) can be asked. Generally, these are verification questions that solicit clarification of facts as well as identify and acquire relevant information, establish communication norms, and mediate interactions.

Deep reasoning questions represent convergent thinking [5–7]. According to Leifer and Steinert, in the convergent phase of design, the designer's goal is to optimize the solution [5]. Graesser and Person [8] note that deep reasoning questions prompt logical, causal, and goal-orientated reasoning. As a result, deep reasoning questions are often prevalent during concept assessment and implementation and function to reduce the number of generated alternatives.

Generative design questions are characterized as divergent thinking. In the divergent phase of design, Leifer and Steinert note that the designer's focus is generally on the problem where they establish an understanding of the user, which elements are involved, generating alternatives to solve the problem, rephrasing, or avoiding the problem [5]. Concepts and ideas are generated thus generative design questions are prevalent when the designer is conceptualizing the problem. As a characteristic of divergent thinking, these types of questions increase ambiguity as the designer generates alternatives and/or reframes needs. Leifer and Steinert add that generative design questions are seen as important for the creation of change as alternatives generated open the solutions space for new ideas to emerge [5].

When we consider questioning as a means to manage convergent and divergent thinking by decreasing or increasing ambiguity, we draw from Eris' [6] definition of ambiguity. Eris describes ambiguity as a "level of conceptual abstraction." To illustrate these levels of conceptual abstraction, Eris uses an example of a car where he notes that it can be described as a transportation device, or as having, as a feature, four wheels. Eris states that the latter description is less ambiguous because it is at a lower level of conceptual abstraction. In our study, we can operationalize Eris' definition of ambiguity in terms of the playground the participants are asked to design. For example, Patrick, one of the playground design experts, asks whether parents are expected to be at the playground, whether there will be supervisors at the playground, or whether the playground is an open public area. Based on Eris' definition, the latter description is less ambiguous as it is at a lower level of conceptual abstraction when compared to the former descriptions. According to Schrader, Riggs and Smith, ambiguity is a state in which one feels one does not know what the relevant variables and their functional relationships are, thus having a lack of clarity in a problem situation [10].

Ambiguity is also viewed as less structured because it is a creative process requiring rethinking of inputs, processes, and outputs.

Eris describes these modes of thinking as engineering design cognition [7]. Drawing from his Divergent-Convergent Inquiry based Design Thinking model (the DCIDT model), Eris explains there are two domains: the concept domain and the knowledge domain. The concept domain represents divergent thinking where questioning is used in order to arrive at possibilities that can be generated from facts. The knowledge domain represents convergent thinking where questioning is used in order to arrive at facts from possibilities [7].

Cardoso and Badke-Schaub [11] have also looked at how design inquiry patterns influence inflection moments, or a particular point in time in the group's design discourse, when designers reflect on the status of the generated ideas, display a level of discontent, and consider alternatives to the current design trajectory. The authors analyzed the design discourse, looking at what happened in moments around question asking. They found high level questions such as Generative Design questions lead to these inflection moments or divergent ideation phases. Question asking behavior has received little attention, but is critical to teaching good design practices.

When we consider questioning in engineering education, Dym, Agogino, Eris, Frey and Leifer make the case that it is important for engineering students to acquire an epistemological inquiry process [10]. For the most part, Dym, Agogino, Eris, Frey and Leifer, and Eris maintain that engineering curricula are designed to successfully help engineering students to engage in convergent thinking, which is characterized by an epistemological approach [7, 10]. This approach emphasizes truth and objectivity where truthfulness can be verified in relation to constraints, assumptions, and scientific principles and the application of the process can be evaluated by identifying relevant principles and analytical steps [7].

In addition to emphasizing an epistemological inquiry process, these authors also argue for engineering students needing to learn how to operate in the concept domain. As engineering students engage in real-world contexts fraught with uncertainty, ambiguity, or with answers that do not hold truth-value, there is an emphasis not only on convergent thinking but also on divergent thinking. In an attempt to expand on this research and address such gaps in engineering design thinking, we resonate with Eris' proposition that "engineering education might be insisting on truth at the expense of conceptual thinking" [7]. Ultimately, we want engineering students to engage in different inquiry processes that equally emphasize increasing ambiguity through divergent thinking and decreasing ambiguity through convergent thinking [7]. In this paper we explore how design experts use their expertise to solve a complex problem through questioning.

2. Methods

In this section, we introduce the participants, data source, method of analysis and the qualitative question codes that will be used throughout the paper.

2.1 Participants

In order to develop an understanding of question-asking behavior in design by comparing three domain experts to three non-domain experts, we present findings from an analysis of six expert designers from two groups. The non-domain expert group consisted of three engineering design experts: Eldon, Elizabeth, and Eric. The domain expert group consisted of three playground design experts: Perry, Patrick, and Phil. The initials of the pseudonyms match the expertise – Engineer pseudonyms begin with *E* and Playground Designer pseudonyms begin *P*. These six expert designers were selected from a previous larger study of 19 engineering experts and four playground design experts (see [12], Mosborg, Adams, Kim, Atman, Turns, and Cardella [13] and Krause, Atman, Borgford-Parnell, and Yasuhara [14] for more details on how experts were identified). In this study, we analyzed three of the four playground experts as one playground expert also had engineering experience. To summarize, experts were practicing professionals who were peer identified as expert designers. The engineering experts were identified through professional networks and were from multiple regions in the U.S., but primarily from the Pacific Northwest. All were screened to ensure that they did not have experience designing playgrounds. The playground designers were not prescreened to ensure that they were not also engineers and were from regions across the U.S.

In addition to studying the design processes employed during problem solving, we also scored the quality of the designed artifact that resulted in a score from 0 to 1 (see Atman, Adams, Cardella, Turns, Mosborg, and Saleem [12] for more details on how quality was assessed.) The engineering expert sample's quality score range was from 0.43 to 0.67 with a mean of 0.54. The three playground designers quality scores were 0.72, 0.60 and 0.58 (for Patrick, Phil and Perry; note these are updated quality scores since the Krause, Atman, Borgford-Parnell, and Yasuhara [14] paper was published). It is notable that the playground design scores from the larger study were all at the high end of the range, or exceeded the quality scores for the engineering experts. We wanted to choose three engineering experts to analyze alongside the three playground experts in our sample – Patrick, Paul and Phil. We chose the engineering experts with the three highest quality scores – 0.67, 0.62 and 0.62 (for Elizabeth, Eric and Eldon).

2.1.1 Design Expert Descriptions

We present the background of each participant (longer descriptions of their approach to the problem are located in Appendix B.) The three engineering design experts' profiles we analyzed were:

- **Eldon:** Male, between 31–40 years of age. He was a Core Tire Pressure Monitoring System Engineer with eighteen years of engineering experience. His background and training were in Electrical Systems Engineering.
- **Eric:** Male, between 31–40 years of age. He was a Lead Engineer for passenger systems with seventeen years of engineering experience. His background and training were in Mechanical Engineer – Design.
- **Elizabeth:** Female, between 41–50 years of age. She was a Consulting Engineer with nineteen and a half years of engineering experience. Her background and training were in Electrical Engineering.

The three playground design experts' profiles we analyzed were:

- **Perry:** Male, between 31–40 years of age. He was a Playscape Designer with fourteen years of professional experience. His background and training were in Industrial Design.
- **Patrick:** Male, between 41–50 years of age. He was a Product Designer with twenty years of professional experience. His background and training were in Industrial Design.
- **Phil:** Male, between 61–70 years of age. He was a Playground Equipment Designer with forty-two years of professional experience. His background and training were in Art, Design, & Child Development.

2.2 Data

The data comes from a previous, larger study using Verbal Protocol Analysis to investigate design behaviour [12]. In order to investigate question-asking behavior, the six participants gave a verbal protocol as they solved a playground design task. While the playground design task was based on a general topic, it was interpretable for all participants regardless of their level of design expertise (see Appendix A for Playground Design task). The participants were given three hours to complete their playground design task. Information made available for the participants included a budget restriction, the area of the playground, material costs (such as wood, piping, sheet metal, chain and rope, miscellaneous hardware, rubber car tires, loose surface material, swing seats, kid tiles, and solid surface materials) neighborhood options, utilities, guidelines for swings, equipment access and platforms, climbing equipment, slides, general safety regulations and the Americans with Disabilities Act, and climate.

2.3 Data Analysis

From the previous larger study, data was transcribed, segmented, time-stamped and coded using the codes based on a set of design process activities [12]. For this paper, data was analyzed by three PhD students, a post-doctoral research associate, a research assistant and a faculty member in Human Centered Design & Engineering at the University of Washington. The data was first analyzed taking a bottom-up approach, thus open coding the transcript. Here, we sought to capture the design experts' realities using in vivo coding (i.e., using participants' own words) and process coding (i.e., observable activities or conceptual actions) [15, 16]. Next, the data was analyzed taking a focused coding approach, which entails identifying the most frequent initial codes and generating categories, or sorting through the codes and looking at code frequencies, relationships between codes and to generate categories [15, 16]. From the generated categories that emerged from the focused coding, we identified and used axial coding [15, 16]. Axial coding entails identifying a core category and its related categories, which is achieved by examining the features and dimensions of categories. Through axial coding, we identified the following categories: "Personal and Professional Knowledge", "Meta-processes", "Questions", and "Assumptions". After several iterations and establishing consensus among the coders on the categories, we focused on the category of "Questions".

Linguistically, questions, as speech acts, have a communicative function and are generally associated with the interrogative syntactic form. While interrogatives perform the communicative function of questioning, other kinds of syntactic forms also do questioning [17]. Ehrlich and Freed [17] note that questions cannot be defined in terms of syntactic form alone. Sidnell [18] maintains that a question is a practice and a category that intersects form and norm. For the purposes of this paper, we define questions as utterances that not only include interrogatives but also solicit information, confirmation or action and convey the assumptions individuals express concerning the norms and social relations that apply in particular settings and contexts [19]. During this coding process, we drew on Dym, Agogino, Eris, Frey, and Leifer [10] and Eris [6] in order to code questions identified in the transcripts. The questions identified were coded using axial coding [15, 16] where we generated themes based on Eris' [6] research. In attending to the multi-functionality of questions, we decided to focus on questions that facilitate converging and diverging thinking.

2.3.1 Codes

The codes represent question function codes that are categorized as (1) decreasing ambiguity (see Table 1) and (2) increasing ambiguity (see Table 2 and 2.1). Questions that related to the study were coded as "Other". In Table 3, the codes represent themes and categories with examples derived from questions that decrease ambiguity (see Table 1).

2.3.1.1 Decreasing Ambiguity

Low-level reasoning questions: The code definition in Table 1 that is characterized as low-level reasoning questions is *Decreasing Ambiguity Nature-Fact* (DANF) questions. Drawing from Aristotle's kinds of questions in Reason, these questions are epistemological in nature thus when considering an object or thing, questions determine whether it is a fact and what the relational reasons are, whether it exists, and what is the nature of the object or thing [6, p. 24].

Deep reasoning questions: The code definition in Table 1 that is characterized as deep reasoning questions is *Decreasing Ambiguity Reasoning* (DAR) questions. Deep reasoning questions converge on facts where the answer to the converging question holds a truth-value.

2.3.1.2 Increasing Ambiguity

Generative design questions: The code definitions that are characterized as generative design ques-

Table 1. Code Definitions for Decreasing Ambiguity with Examples

From Eris [6]	Code	Description
Low-level reasoning questions	*Decreasing Ambiguity Nature-Fact (DANF) Questions*	Relating to aspects of the study; categorized as gathering information; clarifying; factual; and function to decrease ambiguity. E.g. *Is there a – is there a diagram of the corner lot, a scale, or am I making it up?* (Perry, Line 7) *Any kind of maintenance requirements, meaning, uhm, they don't want me to use wood because they got to, you know, maintain that periodically?* (Eldon, Line 216)
Deep reasoning questions	*Decreasing Ambiguity Reasoning (DAR) Questions*	Relating to the facts, the answers hold truth-value and are verifiable. Decreasing ambiguity with a focus on solutions, goals, and reducing the number of alternatives. E.g. *I wondered what the relationship or role of the city with this park would be, not just in maintenance, but also with construction* (Perry, Line 129) *Can I make the assumption that the fence is not required and, therefore – and it is made of wood and is in sufficient condition to use as material?* (Eldon, Line 59)

Table 2. Code Definition for Increasing Ambiguity with Examples

From Eris [6]	Code	Description
Generative design questions	*Increasing Ambiguity (IA) Questions*	Relating to generating possibilities - such as scenario creation, ideation – from facts. Increasing ambiguity in order to establish criteria that informs decision making. E.g. *If they were willing to like bring in some of the equipment or whether they would build or if they have extra funds that they could let go if the neighborhood knocks on the right doors or meets with the right people and so if they could be help with funding or just what role or –* (Perry, Line 129) *And is the grocery store parking lot available for people to park at?* (Elizabeth, Line 18)

Table 2.1. Code Definitions for Increasing Ambiguity Sub-Codes with Examples

From Eris [6]	Code	Description
Generative design questions	*Purview (IA-P)*	Understanding the problem space, boundaries, the situation, and generating ideas *within* the known boundaries. E.g. *surrounding views; role of parents; role of parking lot*
	Reframe (IA-R)	Reframing the problem, pushing back, pushing boundaries, introducing constraints, generating ideas *outside* the known boundaries. E.g. *adding donors; using fencing as materials; building in phases*
	Options-General (IA-OG)	Creating and doing playground ideas. E.g. *shaded areas*
	Options-Specific (IA-OS)	Creating and doing specific equipment elements. E.g. *calculations; dimensions*

tions include *Increasing Ambiguity* (IA) questions in Table 2; and the increasing ambiguity sub-codes *Purview* (IA-P); *Reframe* (IA-R); *Options-General* (IA-OG); and *Options-Specific* (IA-OS) in Table 2.1. The sub-codes in Table 2.1 functioned as increasing ambiguity and were further refined, generating categories listed as sub-codes for increasing ambiguity. Generative questions are characterized as creating knowledge relating to alternative known answers and unknown answers in order to generate answers regardless of their truth value. These diverging questions have multiple answers and can be characterized as speculative. Generative questions are characteristic of divergent thinking, where a design experts' questioning diverges from facts in order to generate possibilities from the facts. Alternatives are generated to establish criteria and inform the decision-making process in design.

In addition, we coded questions as *Other* if they were study-related. Study-related aspects include costs and/or access to information; process orientated; not about the playground object or the playground. For example:

> "*Okay. And how am I supposed to estimate the costs?*" (Elizabeth, Line 489)
>
> "*And then is there any explaining of the design and what the end result is or more the process of it?*" (Perry, Line 362)

2.3.2 Thematic Analysis of Decreasing Ambiguity Nature-Fact (DANF) Questions

Based on the identified question categories, we conducted thematic analysis on questions characterized as decreasing ambiguity (see Table 3) in order to understand the nature of convergent thinking through low-level and deep reasoning questions.

Table 3. Decreasing Ambiguity Nature-Fact Themes and Category Definitions with Examples

DANF Theme	Categories
Understanding situation – people	***Community***: SES information, community demographics, cultural elements, historical aspects, public park, church, daycare program Example: *Do we have any, um, demographics on the nature of the community?* (Phil, Line 24) ***Users***: kids, parents, supervisor, family, teenagers Example: *Would the children be playing there while their parents are at a certain shop* (Patrick, Line 17)
Understanding situation – physical	***Site-related***: lot logistics such as geographic location, size, access; climate; utility information, client, site map; area photographs, playground maintenance, name of park Example: *or are we assuming that everybody is walking from their homes?* (Elizabeth, Line 18) ***Surroundings***: daycare program, church, fence options, sidewalk, parking area, gate Example: *what kind of view from each direction might it be?* (Patrick, Line 10)
Budget/Resources	***Budget***: source of budget, donations Example: *or if they have extra funds that they could let go if the neighborhood knocks on the right doors or meets with the right people* (Perry, Line 129) ***Outsourcing***: using outside expertise Example: *I'm assuming I can take this to my civil friends and have them do calculations, right?* (Elizabeth, Line 256)
Playground specifics	***Playground activities***: balancing; climbing, play activities Example: *what kind of play would they be most likely to engage in?* (Elizabeth, Line 62) ***Playground equipment***: slide; swings Example: *do they want to keep it just specifically to the kids' equipment?* (Patrick, Line 45) ***Non-play items***: items that are not equipment such as benches, sidewalks, garbage cans Example: *Do you have any information on what kind of equipment they might want to have in this area besides the playground itself, like if they might want any park benches or picnic tables or garbage cans or anything like that in the area* (Patrick, Line 44)
Developing Ideas	***Requirements***: ordinance information, zoning, street limitations, equipment restrictions, local building codes, foundation requirements, environmental impact, lighting requirements, standard distances for playground equipment, CPSC requirements, IPEMA information, ADA, playground equipment guidelines Example: *Uhm, is there any local ordinances about, uh, not using certain types of pressure-treated wood or other types of treated things because of the environmental impact?* (Eldon, Line 217) ***Costs***: prices for materials such as circular posts, boulders, hardware, raw materials Example: *is there a materials price list of certain types of materials, wood, uh, metal, things like bark or some kind of – or, uh, bark chips or whatever for ground cover, things like that?* (Eric, Line 57) ***Materials***: material options such as landscaping, wood and metal; strength, size, and durability of materials; playground equipment materials such as swings, swing seats, chains, swing fittings Example: *Any – any information on like kinds of materials in the area or donated kinds of things we could use or bought or taken?* (Perry, Line 66) ***Calculations/modeling***: measuring, dimensions of playground equipment/materials, calculating, modeling Example: *Okay. So then what would be the dimensions of our play structure?* (Elizabeth, Line 157) ***Construction options***: construction crew and availability of skilled labor Example: *Uh, do we have any information about, uh – uh, building assistance, uh, number of volunteers?* (Eldon, Line 150)

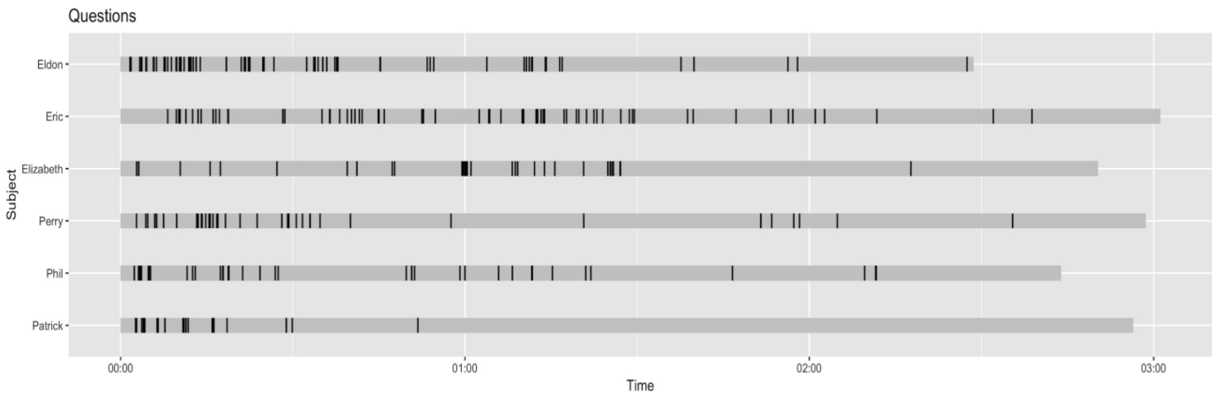

Fig. 1. Timeline of questions for each participant distributed across time.

Consensus among coders was established and discrepancies were verbally resolved.

3. Findings

In this section, we present findings from our analysis of the kind of questioning that goes on in the design process of the participants, including a description of the decreasing ambiguity nature-fact themes that the participants raise through their questions. We include a section that focuses on questions that increase ambiguity, and we describe how participants distribute their questions over time. We end the section with a detailed description of two notable examples of questioning behavior – one engineer and one playground designer.

3.1 Overall Findings on Questions

From the transcripts, we find that all the design experts in our sample ask questions. Fig. 1 displays a timeline for each participant that includes a slash for each question that the participant asked. The timelines show that the participants each spent from 2.5 to 3 hours solving the problem (they were told that they had 3 hours total). The timelines also demonstrate that their questions can occur throughout their design process. More details about how their question-asking is distributed throughout the design process is in section 3.2.5, showing that the questions are predominantly distributed in the first half of their processes.

Table 4 shows the number of questions asked per participant and associated percentages of their overall protocol (as measured in transcript units). The percent of the protocol that was used for questions ranged from 2.8% to 10.8% across the six participants. The percent for the three engineers in our sample was 10.8%, 9.3%, and 3.8%, and for the playground designers in our sample was 9%, 5.5% and 2.8%. Note that in Elizabeth's case, we see from Table 4 and Fig. 1 that she asked the least number of questions among the engineering design experts. Elizabeth was not aware that she could ask the administrator for information until she was a quarter of the way into the protocol.

3.2 Types of Questioning

3.2.1 Decreasing Ambiguity Question Function

Decreasing Ambiguity Nature-Fact (DANF) questions were prevalent for all participants, particularly in the beginning phases of their design process. This dominant question function was also evident throughout the transcripts particularly when the participants were designing specific playground equipment (See Fig. 2). In Fig. 2, across the participants, we see that DANF questions were a dominant question function, ranging from 44% to 69%. *Decreasing Ambiguity Reasoning* (DAR) questions are characteristic of convergent thinking where the questioner attempts to obtain verifiable information [9]. Given the experimental setting and the nature of DAR questions, very few were asked.

3.2.2 Decreasing Ambiguity Question Themes and Categories

In Fig. 3, we represent themes and categories derived from the decreasing ambiguity questions across all design experts. For the theme related to *Understanding situation – people*, the categories include social, cultural, and historical aspects of the community and users. For *Understanding situation – physical*, related categories include aspects

Table 4. Questions as a Percent of Overall Transcript

Name	# transcript units	# question units	% questions
Eldon	677	72	10.8
Eric	700	65	9.3
Elizabeth	834	32	3.8
Perry	490	44	9
Phil	652	36	5.5
Patrick	792	22	2.8

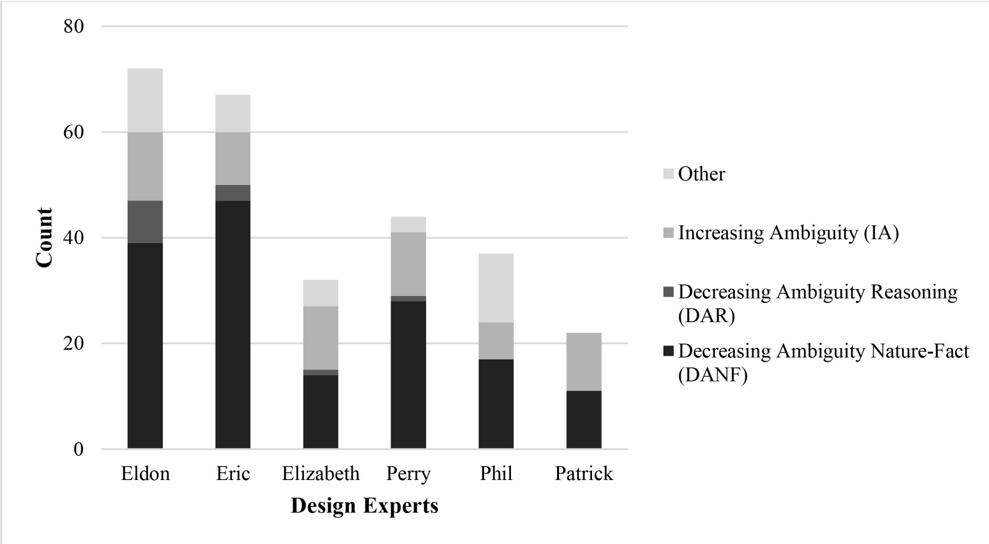

Fig. 2. Count of Decreasing and Increasing Ambiguity Questions.

that are site-related and the surroundings. For *Budget/Resources*, related categories include the budget and also outsourcing. For *Playground specifics*, related categories include playground activities, playground equipment, and non-play items. Finally, for the theme *Developing Ideas*, related categories include requirements, costs, materials, calculations or modeling, and construction options. In addition to Fig. 3, Table 3 provides a detailed description of the themes with examples.

3.2.3 Decreasing Ambiguity Nature-Fact (DANF) Question Themes

Among the Engineering design experts, Eric and Eldon posed the most *Decreasing Ambiguity Nature-fact* (DANF) questions and from the Playground experts, Perry and Phil posed the most DANF questions. For the Engineering Design Experts, DANF questions were predominantly based on building codes, equipment and material guidelines, safety requirements, and American Disabilities Act regulations.

For Eldon, DANF questions entailed information related to aspects for developing ideas such as:

- Zoning

  "*Okay. Seeing as I'm asked by the City to do this, am I to assume that it's zoned appropriately?*" (Line 44)

- Local Building Codes

  "*Uhm, do we have, uh, local building codes that I have to, uh, comply with?*" (Line 175)

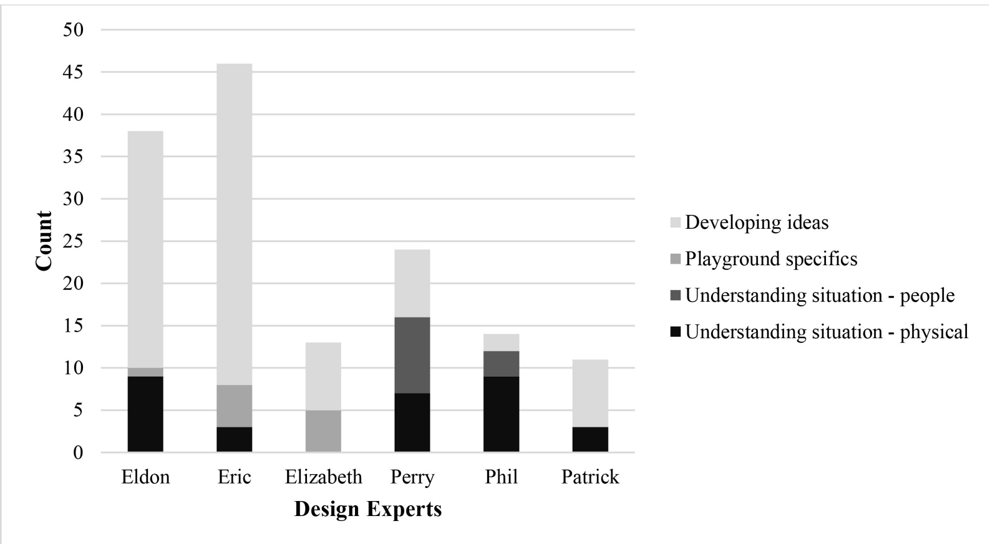

Fig. 3. Count of Decreasing Ambiguity Nature-Fact Question Themes.

- Ordinance Information

  "*Uh, any ordinance information like height, uhm, limitations, limitations relative to, uh, any easements that I have to worry about for the property, uhm*" (Line 16)
- Utility Information

  "*mean, any – any kind of utility, you know?*" (Line 35)

  "*You stated water and power, but is there sewage lines*" (Line 36)

For Elizabeth and Eric, DANF questions were predominantly related to playground specifics and developing ideas that entail equipment and material guidelines as well as safety requirements. In terms of equipment, information related to safety distances for swings and for anchoring equipment were requested during the design of equipment as evidenced in the following quotes:

- Playground Specific Examples

  "*Are there any sort of standard distances for things like swings that we're given*" (Elizabeth, Line 324)

  "*how far to bury posts into the ground for minimum safe distances for burying concrete or burying things, anchoring?*" (Eric, Line 465)

DANF or fact-finding questions related to safety requirements were asked in the early phases of the design process. For example, information related to the American Disabilities Act as illustrated in the following excerpt:

- Fact Finding and Safety Example

  "*Uhm, do you have information on the American Disabilities – Americans for Disabilities Act, some rules, regulations regarding accessibility*" (Eric, Line 88)

In addition to information related to regulations, the engineer design experts requested information related to particular playground equipment (during the modeling phase). For example,

- Playground Equipment Example

  "*Do you have any minimum guidelines for climbers and forts and slides, slopes, angles, appropriate angles?*" (Eric, Line 385)

The engineering design experts were also concerned about the budget and costs of materials for equipment such as lumber, hardware, or under piping. For example,

- Budget Example

  "*Do I have a price that I'm allowed to work with or a budget?*" (Eric, Line 55)

In addition, the engineering design experts made inquiries about the dimensions of equipment or structures as well as the durability of materials. Materials and types of playground equipment were also prevalent.

For the playground experts, we found that fact finding questions were predominantly based on community aspects. For example, both Phil and Perry requested information related to community demographics. Phil requested more general information related to the surroundings of the lot, such as "*a daycare program*" (Line 75), whether there was a church (Line 163) and socioeconomic information as illustrated in Lines 24 and 25:

> "*Do we have any, um, demographics on the nature of the community?*" (Phil, Line 24)

Perry requested more specific information:

> "*Well, who lives in the multifamily homes and apartments, what their – I don't know, socioeconomic info is or what part of the town or is it – are there cultural – different types of cultural elements or history of the people that we might want to blend into the playground?*" (Perry, Line 22).

Other community aspects accounted for included the age range (Perry, Line 111) and whether there were meeting minutes related to the public park; for example:

> "*So, of course, the great thing to do early on is have meetings with the people in opening – open that up to discussion, so I would wonder if there are any minutes from any meetings or any requests, people to talk to*" (Perry, Line 39).

Other aspects such as understanding the situation in relation to physical aspects included lot logistics which entailed location ("*Where – where is this city geographically*" Perry, Line 27), climate ("*as far as like is it down south, is it – thinking about like weather and the seasons*" Perry, Line 28), and size of lot ("*Is there a – is there a diagram of the corner lot, a scale, or am I making it up?*" Perry, Line 7). Construction options were also considered; for example, "*How many people have I got that can build this?*" (Phil, Line 386).

3.2.4 Increasing Ambiguity Questions (IA) and Sub-Codes

3.2.4.1 Increasing Ambiguity (IA) Questions

From Fig. 2, the second largest category of question function across participants is *Increasing Ambiguity* (IA) questions, ranging from 15% to 38%. Across the participants, we find that questions that increase ambiguity generate possibilities; thus, the participants engage in divergent thinking in order to generate options. A closer examination of questions that increase ambiguity shows that for each participant, these questions are characterized in different ways.

3.2.4.2 Increasing Ambiguity Questions Sub-Codes

Through our analysis we investigated increasing ambiguity questions in further detail observing instances of *Option-General*, *Option-Specific*, *Reframe*, *Purview*. In these instances, we see in Fig. 4 how the design experts use divergent thinking in various ways. Across the engineering design experts, *purview*-type questions were distributed in various ways, while Patrick is the only playground design expert that used *purview*-type questions. Across the playground experts *reframing*-type questions were distributed in various ways.

Fig. 4 shows the distribution of the *Increasing Ambiguity* questions of each expert as they relate to the sub-codes. The engineering design experts consistently include more *purview*-related (ranging from 17% to 33%), *options-general* (ranging from 8% to 40%) and *options-specific* questions (ranging from 25% to 58%). Recall that the *purview* questions (IA-P) relate to understanding the problem space, boundaries, the situation, and generating ideas within the known boundaries. *Options-General* (IA-OG) questions relate to creating and doing playground ideas and *options-specific* (IA-OS) questions relate to creating and doing specific equipment elements. The *purview*-related questions generally include inquiries related to the following:

- Materials

  "*Is there any other assumptions I can make about, uh, existing materials that might be available for little or no costs? Uhm, things like telephone poles, uhm, or any kind of utility poles to use.*" (Eldon, Line 234)

- Construction options

  "*Uh, do we have any information about, uh – uh, building assistance, uh, number of volunteers?*" (Eldon, Line 150)

- The user(s)

  "*And is the grocery store parking lot available for people to park at*" (Elizabeth, Line 18)

- Accessibility

  "*or are we assuming that everybody is walking from their homes?*" (Elizabeth, Line 18)

- Budget

  "*What else do I need?*" (Eric, Line 85) – In context, the question refers to material costs with budget constraints.

The *options-general* and *options-specific* questions deal with equipment (e.g., "*And, you know, in my head I'm thinking, well, how do I build a slide without purchasing a slide?*" Eldon, Line 75) and calculating the dimensions of equipment (e.g., "*what else we would need dimensions on*" Eric, Line 375; "*How far in front of these swings do we need to have free space?*" Elizabeth Line 460). In these instances, these questions were asked in the second quartile of the transcripts.

The playground experts had predominantly *reframing*-type questions, ranging from 20% to 92%. The reframing questions were primarily related to budget (e.g., "*Are there any – are there any donors that can be approached for grants and gifts?*" Perry, Line 66), construction options (e.g., "*Would they be interested in building in phases?*" Perry, Line 118), and materials (e.g., "*Is there any access to free material, such as blocks or broken concrete or any of that kind of stuff?*" Phil, Line 181).

A closer examination of how the design experts use divergent thinking in various ways is illustrated in Eric's and Eldon's cases for the engineering design experts and in Patrick's and Perry's cases for the playground design experts. In these cases, Eric did not pose reframing questions whereas Eldon poses a range of divergent questions. Patrick

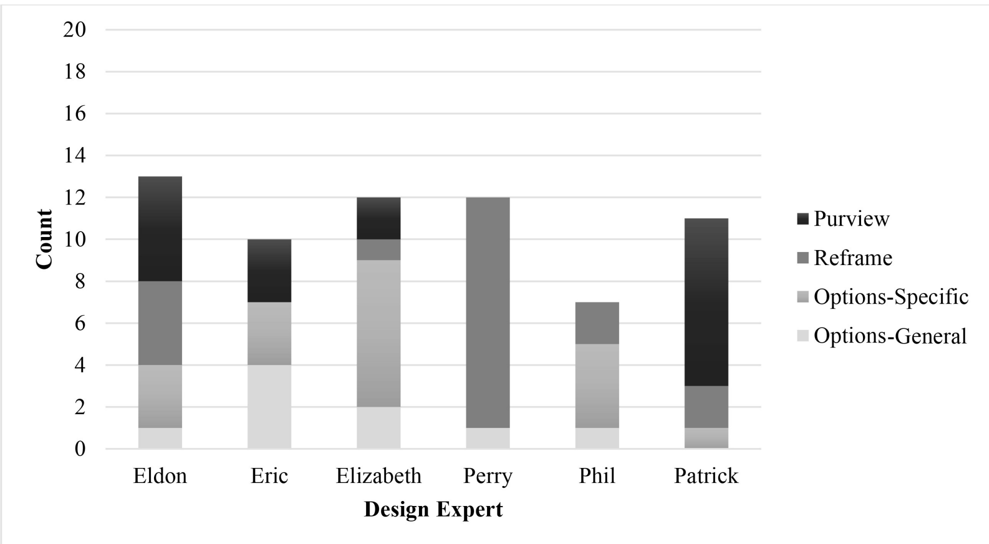

Fig. 4. Increasing Ambiguity Sub-Code Counts.

also posed a range of divergent questions whereas Perry posed the most reframing questions

Eric: Eric takes an open-ended approach where he creates no determined boundaries when posing *purview* questions, *options-general* and *options-specific* questions. His purview questions attend to topics about the budget and materials; and his options-related questions consider topics about the equipment and calculations (modeling). In the transcript, we see that these questions are distributed across the first and second quartiles.

In order to generate ideas about the budget and materials, Eric's purview questions enable him to explore options when he consistently poses the same purview questions about the **budget and materials**:

> "*What else do I need?*" (Line 85)

We also see this kind of inquiry extend to his options-general questions about the calculations and equipment. In these instances, he takes the same approach as he does with the purview questions but articulates them differently, as illustrated in the following options-general question about **equipment**:

> "*What other kind of playground things would be fun?*" (Line 246)

Eric consistently generates options even in specific instances related to equipment throughout his design process. For example, as he negotiates needs, he generates possibilities as he considers how to carry out his **calculations on swings:**

> "*what else we would need dimensions on*" (Line 375)

This kind of questioning is also evident when considering options for equipment where he determines the constraints when asking for guidelines related to equipment and then generates options within those constraints.

Eldon: Throughout the design activity, Eldon poses a range of IA questions that include both *reframing* and *purview* types of questions and *options-specific* questions. As Eldon evaluates the problem, he asks reframing questions related to materials and the budget in order to negotiate possibilities; for example:

> "*Uh, is the – is the fence – okay, you must not have any information about the fence 'cause what I'm wondering is the fence in sufficient condition that we should plan to remove it or not?*" (Line 55)

> "*can I use a junkyard for tires and things like that?*" (Line 98)

In discerning needs and generating possibilities related to materials, Eldon also negotiates the constraints of the budget:

> "*Okay. Am I allowed to solicit donations? Am I allowed to solicit donations from the community?*" (Line 230)

As he generates options, such as soliciting donations from community, Eldon also poses purview-type questions that relate to materials, construction options and the user. These questions entail project management aspects as illustrated in the following quote related to construction options:

> "*Uh, do we have any information about, uh – uh, building assistance, uh, number of volunteers?*" (Line 150)

In addition to reframing budget and material options, Eldon also seeks to negotiate and define the scope of the problem by considering materials in relation to costs:

> "*Is there any other assumptions I can make about, uh, existing materials that might be available for little or no costs? Uhm, things like telephone poles, uhm, or any kind of utility poles to use.*" (Line 234)

In relation to the materials, Eldon poses option-specific questions related to equipment for the playground:

> "*And, you know, in my head I'm thinking, well, how do I build a slide without purchasing a slide?*" (Line 85)

In dealing with incomplete information, Eldon considers equivalent materials thus continually generating options in the types of questions he poses.

Patrick: For the most part, Patrick poses *purview*-related IA questions about the surroundings and the user. We see that these questions are distributed in the first quartile of the transcript which suggests he is determining factors that might influence his choices while considering the different layers of the problem statement. For example:

> "*what's nearby that borders the lot.*" (Line 8)

> "*what kind of view from each direction might it be?*" (Line 10)

Questions posed about the surroundings also has implications for the user and the design of the playground where options are generated in a relational manner. Based on information gathered about the surroundings, Patrick shifts his focus to the user:

> "*Would the children be playing there while their parents are at a certain shop*" (Line 17)

> "*is it something that the parents would be expected to be there with them*" (Line 18)

> "*would there be supervisors at the playground*" (Line 18)

At the same time, Patrick considers the equipment in relation to the user by asking whether non-play structures would be considered along with playground equipment, again broadening his options:

> "*Do you have any information on what kind of equipment they might want to have in this area besides the playground itself, like if they might want any park benches or picnic tables or garbage cans or anything like that in the area*" [Coded as NON-PLAY] (Line 44)

"*do they want to keep it just specifically to the kids' equipment?*" [Coded as EQUIPMENT] (Line 45)

As Patrick considers the relational aspects of the surroundings, the user, the non-play structures and playground equipment, this also suggests that he is determining a functional relationship between these aspects since they are unknowns. For Patrick, we see that his purview-related questions take the perspective of the user and he generates options by discerning needs and possibilities, which could be useful in making design decisions and developing strategies.

Perry: Perry was a notable case in that he asked the most *reframing* questions. The reframing questions included topics about the user, budget, construction options, materials and surroundings. We find that these questions are distributed in the first and second quartiles of the transcript. With IA questions only in the first half, there are several notable sequences of reframing. In relation to reframing, Perry considers the following factors:

- User

  "*So how can you invite people in but at the same time let people know that it's a special place*" (Line 56)

- Budget

  "*Okay. Are there any – are there any donors that can be approached for grants and gifts?*" (Line 66)

- Materials

  "*Any – any information on like kinds of materials in the area or donated kinds of things we could use or bought or taken?*" (Line 69)

- Construction Options

  "*Would they be interested in building in phases?*" (Line 118)

  "*if they were willing to like bring in some of the equipment*" (Line 129)

  "*or whether they would build*" (Line 129)

Looking across the spread of playground and engineering design experts, we find a range of variability at this level of detail. *Decreasing Ambiguity Nature-Fact* (DANF) questions were prevalent for all participants, particularly in the beginning phases of their design process. For the engineering design experts, DANF questions were predominantly based on building codes, equipment and material guidelines, safety requirements, and American Disabilities Act regulations. For the playground experts, we found that DANF questions were predominantly based on community aspects. The second largest category of question function across participants is *Increasing Ambiguity* (IA) questions. The engineering design experts consistently include more *Purview*-related (IA-P), *Options-General* (IA-OG) and *Options-Specific* (IA-OS) questions. The playground experts had predominantly *reframing*-type (IA-R) questions.

Across participants, we better understand the nuanced types of expertise within each type of expert and the question asking process. Among the engineering design experts, only Eldon and Elizabeth had instances of increasing and decreasing ambiguity. Eldon had the most even distribution across the increasing and decreasing ambiguity question codes. Elizabeth had an *Options-Specific* focus and Eric had an *Options-General* focus. Among the playground design experts, Perry had a *reframing* focus; Patrick had a *purview* focus; and Phil had an *Options-Specific* focus.

3.2.5 Participants' Distribution of Questioning Over Time

In order to understand question-asking as part of the design process, we looked at the distribution of question-asking over time. In Fig. 5, we represent our participants' questions over time that are based on bins for each 10% of each participants' total time (approximately three hours for each participant). Over time, we see that the questions are heavily distributed in the beginning of the design process, consistent with the idea that it is important to understand the problem one is solving before moving into an ideation and modeling phase (see [12]). While Fig. 5 demonstrates that all the participants ask questions early, it is notable that five of the participants also asked a few questions throughout the rest of the process (Eldon, Eric, Elizabeth, Perry and Phil). Several patterns are notable: Patrick asked all his questions up front, and Eric and Elizabeth more consistently distributed their questions throughout their problem-solving process. Recall that in this lab-based experimental situation Elizabeth had not initially understood that she could ask questions of the experiment administrator, and this could have altered her question-asking behavior.

A closer examination of the kinds of questions participants are asking show that the early questions are predominantly *decreasing ambiguity nature-fact* (DANF) questions. As participants initially decreased ambiguity during the first part of the design process, we also saw instances where they increased ambiguity through their questions. In these instances, questions that increase ambiguity are distributed among the DANF questions thus, as participants decrease ambiguity with DANF questions, they are also posing questions that increase ambiguity in order to generate options for their design. An investigation of the questions that increase ambiguity as they relate to the sub-codes, we see that *purview*-type questions are used during the first part of the process. The *options*-type ques-

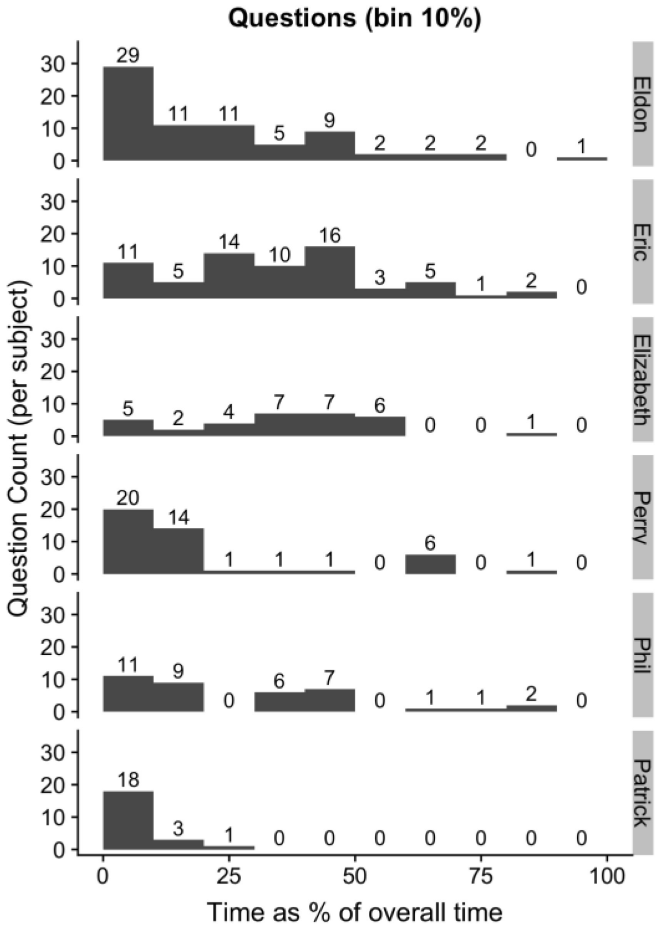

Fig. 5. Distribution of questions over time.

tions tend to be asked in the latter part of their process as they work on particular aspects of their designs.

3.2.6 *Two Notable Examples: Eldon and Perry*

In our notable cases, Eldon and Perry were selected because they had the highest percentage of questions for their category of expertise (Eldon for the engineering and Perry for the playground designers). We also see that these participants have compelling distributions of question types across their design process (see Figs. 6 and 7).

In Figs. 6 and 7, we present three timelines based on our question function codes; that is, *decreasing ambiguity nature-fact* (DANF), *decreasing ambiguity reasoning* (DAR), *increasing ambiguity* (IA), and *Other*. The next set of timelines represent the increasing ambiguity sub-codes; that is, *purview* (IA-P), *reframing* (IA-R), *options-general* (IA-OG) and *options-specific* (IA-OS). The final set of timelines are drawn from codes that represent design process activities. For an in-depth description of the timeline representation of these individual design processes, see Atman, Adams, Cardella, Turns, Mosborg, and Saleem [12]. The design activity codes in the timeline are Problem Definition (PD), Gather Information (Gath); Generate Ideas (Gen), Model (Mod), Feasibility Analysis (Feas), Evaluation (Eval), Decision (Dec), Communication (Com), and Study Administration (Admin).

3.2.6.1 *Eldon's Distribution of Questioning Over Time*

When we consider Eldon, we find that he posed all the increasing ambiguity sub-code questions (i.e., *Purview*, *Reframing*, *Options-General* and *Options-Specific*), as did Elizabeth, Eric, and Perry. While Eldon's questions were front heavy, we chose to highlight his question-asking process because he had questions across all quartiles. For example, referring to Fig. 6, we see he asks questions that increase ambiguity across all quartiles. A notable sequence in the beginning of the transcript of *Reframe*, *Purview*, *Options-Specific* shows how Eldon begins his process by posing *decreasing ambiguity nature-fact* (DANF) questions. He first considers lot logistics such as climate and water, and then ordinance information; for example

"*Uh, any ordinance information like height, uhm, limitations, limitations relative to, uh, any easements that I have to worry about for the property, uhm,*" (Line 16)

"*meaning do I have to have a certain standoff from Pine Street and Second Avenue, those kinds of things.*" (Line 17)

After obtaining information that relates to city ordinances and requirements, Eldon then asks whether the fence should remain and then begins to generate choices by posing increasing ambiguity questions as he considers the types of materials for the fence asking a *reframing*-type question:

"*Really, so that's an either/or. Uh, is the – is the fence – okay, you must not have any information about the fence 'cause what I'm wondering is the fence in sufficient condition that we should plan to remove it or not?*" (Line 55)

As he considers the condition of the fence, he also asks *purview*-type questions:

"*What is it made out of?*" (Line 55)

We see a similar type of approach when he considers building a slide, where he first increases ambiguity asking *Option-Specific* types of questions:

"*And, you know, in my head I'm thinking, well, how do I build a slide without purchasing a slide?*" (Line 81)

Next, he decreases ambiguity in order to check what is and is not permissible by asking, "*am allowed to use that as material?*" (Line 92). When we consider Eldon's increasing ambiguity sub-code questions in relation to the design process activity codes, we see that approximately half of his questions that increase ambiguity are related to gathering information, under half of his questions are related to generating ideas, feasibility, and modeling.

3.2.6.2 Perry's Distribution of Questioning Over Time

Among the playground design experts, Perry was regarded a notable case as he had posed many *reframing*-type questions that increase ambiguity. As seen in Eldon's case, we see in Fig. 7 that Perry's questions were also front heavy but had questions across all quartiles. Perry considers the value of the playground for the community and in doing so extends the purpose of the playground, as illustrated:

"*So how can you invite people in but at the same time let people know that it's a special place*" (Line 56)

In considering the budget, we see that Perry begins negotiating possibilities by asking, "*So does this project have to fall within that budget?*" (Line 64). In doing so, he develops what Schön calls "on-the-spot-variations" [19]. This is exemplified in the following reframing question that increase ambiguity:

"*Okay. Are there any – are there any donors that can be approached for grants and gifts?*" (Line 66)

Perry reframes the budget constraint and generates alternative budget options – approaching donors. Subsequently, he extends on his budget options to include materials thus further generating possibilities:

"*Any – any information on like kinds of materials in the area or donated kinds of things we could use or bought or taken?*" (Line 69)

Alternative budget options also extend to construction options. Perry again begins negotiating possibilities by asking, "*Would they be interested in building in phases?*" (Line 118) In relation to the construction option, Perry considers additional

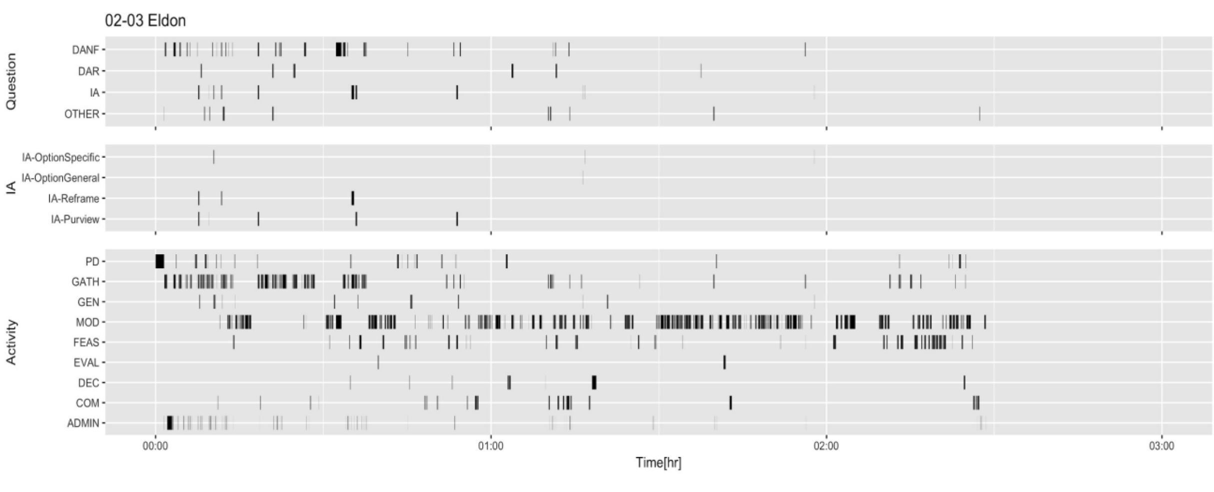

Fig. 6. Eldon's Distribution of Questions Over Time.

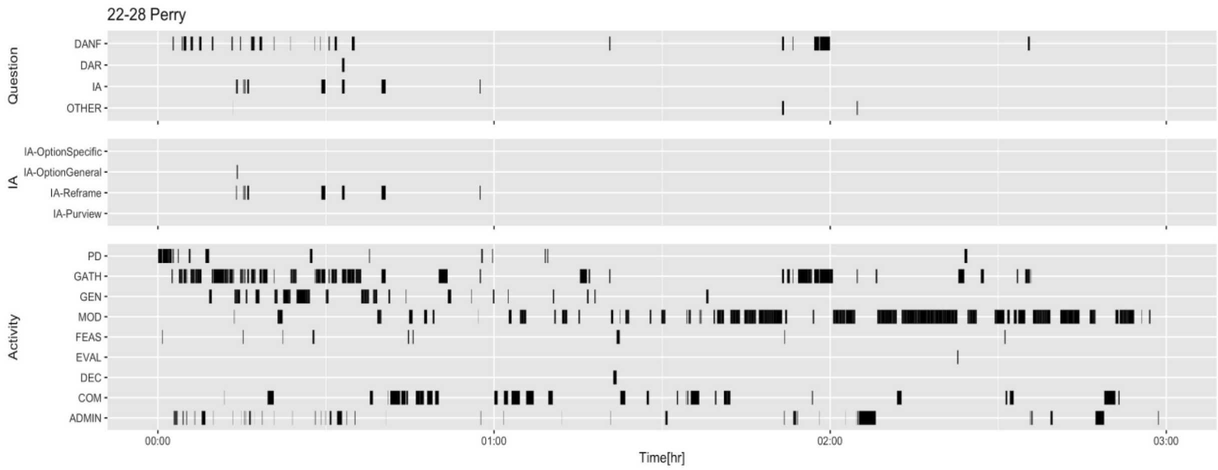

Fig. 7. Perry's Distribution of Questions Over Time.

alternative methods related to donors for obtaining extra funds:

> "*I wondered what the relationship or role of the city with this park would be, not just in maintenance, but also with construction, if they were willing to like bring in some of the equipment or whether they would build or if they have extra funds that they could let go if the neighborhood knocks on the right doors or meets with the right people and so if they could be help with funding or just what role or –*" (Line 129)

We see from these instances that Perry uses reframing questions in order to generate options that go beyond the boundaries of the problem setting. When we consider Perry's questions that increase ambiguity in relation to the design activity codes, we see that Perry generates ideas and gathers information when asking his questions.

To summarize, we find that all the design experts in our sample ask questions and that their questions occur throughout their design process. The percent of time spent on questions posed by Eldon, Eric and Elizabeth, the engineering design experts, ranged from 10.8%, 9.3% and 3.8%, respectively; and by Perry, Phil and Patrick, the playground design experts, was 9%, 5.5% and 2.8%, respectively.

Decreasing Ambiguity Nature-Fact (DANF) questions were prevalent for all participants in our sample, particularly in the beginning phases of their design process. Among the engineering design experts, Eric and Eldon posed the most DANF questions and from the playground experts, Perry and Phil posed the most DANF questions. For the engineering design experts, DANF questions were predominantly based on building codes, equipment and material guidelines, safety requirements, and American Disabilities Act regulations. For the playground design experts, we found that DANF questions were predominantly based on community aspects in order to understand the social and physical situation. *Decreasing Ambiguity Reasoning* (DAR) questions were seldom posed due to the experimental setting (i.e., a lab-based setting where participants gave a verbal protocol as they solved a playground design task) and the nature of DAR questions.

Increasing Ambiguity (IA) questions was the second largest category of question function across participants, ranging from 15% to 38%. The engineering design experts consistently include more *purview*-related (ranging from 17% to 33%), *options-general* (ranging from 8% to 40%) and *options-specific* questions (ranging from 25% to 58%). The playground experts posed predominantly *reframing*-type questions, ranging from 20% to 92%. Across participants we see more nuanced types of expertise within each type of expert and the question asking process. Among the engineering design experts, Eldon had the most even distribution across the increasing and decreasing ambiguity question codes; Elizabeth had an *Options-Specific* focus; and Eric had an *Options-General* focus. Among the playground design experts, Perry had a *reframing* focus; Patrick had a *purview* focus; and Phil had an *Options-Specific* focus.

Over time, we see that the questions are heavily distributed in the beginning of the design process. We found two patterns of contrast where the playground experts, notably Patrick and Perry, asked all their questions up front, and with the engineering design experts, Eric and Elizabeth spread their questions throughout. The kinds of questions participants are asking show that the early questions are predominantly DANF questions, thus decreasing ambiguity during the first part of the design process. In instances where the design experts increased ambiguity through questioning, the increasing ambiguity questions are distributed among the DANF questions.

From the question sub-codes that increase ambiguity, we see that *purview*-type questions are used during the first part of the process and the *options*-type questions tend to be asked in the latter part of their process. In our notable cases, Eldon and Perry have compelling distributions of question types across their design process. Eldon had questions across all quartiles, posed all the question sub-codes that increase ambiguity and his questions were front heavy. Perry had the most questions that entailed *reframing* and his questions were also front heavy and distributed across all quartiles.

4. Discussion and Implications for Teaching

The objective of this study was to develop an understanding of question-asking behavior in design by comparing three domain experts to three non-domain experts. Looking across the spread of playground and engineering design experts we find a range of variability in the kinds of questions posed. *Decreasing Ambiguity Nature-Fact* (DANF) questions were prevalent for all participants, particularly in the beginning phases of their design process. The second largest category of question function across participants is *Increasing Ambiguity* (IA) questions. As the design experts initially decreased ambiguity through questioning during the first part of the design process, they also increased ambiguity through questioning to generate options for their design. When considering questions that increase ambiguity as they relate to the question sub-codes, we see that *purview*-type questions are used during the first part of the process and *options*-type questions tend to be asked in the latter part of their process as they work on particular aspects.

For the engineering design experts, DANF questions were predominantly based on building codes, equipment and material guidelines, safety requirements, and American Disabilities Act regulations. For the playground experts, we found that DANF questions were predominantly based on community aspects. From these results, what differentiates non-domain experts from domain experts is the kind of constraint they choose to focus on. Both the engineering design experts and playground experts pose converging questions initially in order to determine needs, define requirements, and gather information. However, the engineering design experts focus on the technical aspects of the playground design task whereas the playground experts focus on the social contextual factors. Research from Krause, Atman, Borgford-Parnell, and Yasuhara [14] corroborates this finding where the playground experts considered the social context more than the engineering design experts, thus highlighting not only the role of context but also what the design experts deem important. For the playground experts, the user and community are the most important factors to consider as opposed to what matters for the engineering design experts. Based on Krause, Atman, Borgford-Parnell, and Yasuhara [14] findings, these differences in what matters could be attributed to experience and the kinds of knowledge used. With domain experience and professional knowledge, the playground experts made broader contextual and social connections. The engineering design experts used engineering professional knowledge and personal playground knowledge to add to the details given to them during the task. Of consequence here is, as Schön [20] poses, what must design experts know, what kinds of expertise, what features of stance towards practice, must they have acquired in order to describe what they know how to do, justify it as a legitimate form of professional knowledge, increase its scope or depth or quality, and translate and transfer for learning.

Increasing Ambiguity (IA) questions were the second largest category of question function across the participants. While the engineering design experts consistently include more *purview*-related (IA-P), *options-general* (IA-OG) and *options-specific* (IA-OS) questions, the playground experts had predominantly *reframing*-type (IA-R) questions. Across participants we see differences in the types of expertise within each type of expert and the question asking process. Eric did not pose reframing questions whereas Eldon poses a range of divergent questions. Patrick also posed a range of divergent questions whereas Perry posed the most reframing questions.

The various increasing ambiguity questions posed to generate possibilities derived from facts in order to establish criteria and inform choices are characteristic of divergent thinking. This is illustrated in Eldon's and Perry's cases, our notable examples, and in relation to the design process activity codes. Approximately half of Eldon's questions that increase ambiguity were posed when gathering information, and under half of his questions were posed when generating ideas, checking feasibility, and modeling. After understanding the physical situation related to the site and developing ideas related to requirements, Eldon focuses on developing ideas related to materials by increasing ambiguity as he poses *reframing* questions to generate and negotiate options.

By understanding and reframing boundaries of the problem setting, Perry increases ambiguity by posing *reframing* questions to generate ideas and gather information about the user, budget, materials, and construction options. From an epistemological perspective, reframing enables design experts to consider the problem setting or constraint from another perspective. Strategies, heuristics or best practices enable design experts to navigate the problem setting by introducing new variables, parameters or concepts that lead to new conjectures. Generative design questions that increase ambiguity enable experts to explore the problem setting without necessarily needing a-priori domain knowledge. The existing and tacit knowledge experts bring to the problem setting is iteratively re-shaped and re-validated as they navigate their solutions to problems and new solutions or relations become apparent. Thus, in a diverging strategy where alternatives are generated, experts consider the causal relations between the functions and structures of an aspect in the problem setting which then get transformed and elaborated upon within the given design situation [21]. In a design activity, Schön [22] describes these design moves as situational transactions where the design expert *shapes the situation*, the situation *talks back* and the design expert responds to the situation's *back-talk*. Reframing the design situation is viewed as a reflective process where Schön's [22] notion of *reflection-in-action* is relevant for understanding and investigating the design situation further.

The situational transaction described above is illustrated across participants where we see that the kinds of questions posed during the first part of the design process are predominantly *Decreasing Ambiguity Nature-Fact* (DANF) questions, thus the experts decrease ambiguity as they gather information through clarifications and facts. In instances where increasing ambiguity questions are posed, we see they are distributed among the DANF questions. Based on the design experts' perspective and focus, questions that increase ambiguity such as *purview*-type questions are used during the first part of the process and the *options*-type questions tend to be asked in the latter part of their process. As the design experts generate alternatives, the *purview*-type questions establish an understanding of the problem space, the boundaries, the situation and alternatives are generated within the known boundaries. *Purview*-type questions in this study were posed during the first part of the process in order to establish a global understanding or (re)framing of the design situation. Options-type questions were posed in the latter end. The *options-general* type questions relate to creating and doing playground ideas and the *options-specific* type questions relate to creating and doing specific equipment elements. The options-type questions establish an understanding or (re)framing of the playground specifics such as playground activities, playground equipment and non-play items as well as an understanding or (re)framing of the costs, materials, calculations, modeling, and construction. For this study the generative design questions function similar to increase ambiguity by reframing, understanding the problem space with alternatives within known boundaries, negotiating ideas, objects, activities and technical aspects. The distribution of the kinds of questions posed over time across the design experts shows the various ways that the design experts managed ambiguity. In our notable cases, Eldon and Perry have compelling distributions of question types across their design process. Eldon had questions across all quartiles, posed all the question sub-codes for increasing ambiguity and his questions were front heavy. Perry posed many *reframing* questions and his questions were also front heavy and distributed across all quartiles. Working with incomplete information, Eldon's ambiguity is managed in relation to developing ideas based on the technical aspects of the design problem. Perry's ambiguity is managed in relation to understanding the social situation in the context of the physical aspects. Across participants we see differences in how questions function to decrease or increase ambiguity.

If we look more specifically at asking effective questions during a design process - we can recognize that it is a skill that can be specifically taught. What constitutes good questioning practices in design? What we observed from the experts we studied in this analysis is that experts ask questions that move their design process forward. While most of the questions they ask are in the initial problem scoping phase of design, they also ask questions throughout the design process. The questions that experts ask vary in their function. More specifically, they vary in how they deal with ambiguity. A majority of the questions we observed our experts ask decreased ambiguity – mostly by fact finding during the initial problem scoping stage. However, questions also play an important role for increasing ambiguity – helping them to understand and reframe the problem and help generate options. In this manner the experts in this study used questions to help them understand and push problem boundaries as they engage in both convergent and divergent design behaviors.

4.1 Implications for Teaching

Overall, when we consider the teaching implications of this work and how we can include both divergent and convergent thinking in engineering design cognition, Eris highlights some issues and suggestions. In terms of issues, Eris highlights assessment and how instructors may objectively grade the conceptualization performance of engineering students when they are subjective in nature [7]. Another issue relates to how engineering students manifest their modes of thinking. For Eris, the use of notebooks comes with affordances for supporting engineering students' convergent and divergent thinking processes. Another means for supporting engineering students' design cognition is through portfolios. Eris suggests asking students to formulate, explore, and document generative design questions that increase ambiguity related to the subject they are studying in their engineering portfolios. By having engineering students engage in different inquiry processes, the engineering portfolios would have conceptual sections that address increasing ambiguity through divergent thinking, and knowledge-based sections that address decreasing ambiguity through convergent thinking [7].

Paying attention to these epistemological-level and conceptual-level questions, we may support students' modes of thinking by distinguishing between the degree to which these questions are open-ended. For example, Cunningham [23] distinguishes between low- and high-convergent and divergent questions. Low-convergent questions have a similar function as the low-level reasoning questions illustrated in our code for *decreasing ambiguity nature-fact* (DANF) questions; and high-convergent questions have a similar function as the deep reasoning questions illustrated in our code for *decreasing ambiguity reasoning* (DAR) questions. These kinds of questions are related to knowledge and facts, which are routinely used in textbooks and highlight the kinds of reasoning (i.e., generating inferences, interpretations or generalizations) students are engaging in [23]. Low-divergent questions have a similar function as the generative design questions, in particular our *increasing ambiguity* (IA) questions, where alternative ways to do something are generated. High-divergent questions also have a similar function as generative design questions, as illustrated in our increasing ambiguity sub-codes: *purview, reframe, options-general and options-specific*. These kinds of questions are conceptually abstract and, as Eris and Dym, Agogino, Eris, Frey, and Leifer ([7, 10]) note, are often not integrated in engineering curricula. Providing engineering students with opportunities to operate in the concept domain requires built-in time to have students explore ideas without having to give correct answers. Having students think broadly and explore possibilities enhances their conceptual understanding as they develop plans or strategies, propose tentative solutions, speculate about possible outcomes or make conjectures using prior knowledge or from the situation's back-talk [22]. One way to support students in asking low- and high-divergent questions could entail having students go through the mental experience of exploring different ideas through questioning [23]. Another way is by having students start with low-divergent questions, questions that increase ambiguity, in a design task to brainstorm possibilities and then shift to high-divergent questions by thinking of the content and context of the design situation in different, creative ways. Creative thinking techniques that scaffold students' understanding of the design situation and broaden the boundaries of a problem could be accomplished in many ways. Lawson [24] offers a practical approach where design problems and their problematic relationships are identified and simplified in order to expand on a problem. During this process, the people or things involved in the design situation are related by *conflict*, from different points of view (i.e., a *contradiction*), a *complication, chance* or a *similarity*. Providing students with opportunities to engage in convergent and divergent thinking through questioning enables students to initially develop perceptions, initiate actions and shift their design situation from lower to higher levels of conceptual abstraction. Consequently, students manage ambiguity by processing information in different ways while also making contributions to their own learning about their design process and outcomes that are personally consequential.

How can we translate these observations into practical activities in the classroom? We can make this one of the things we asked students to pay attention to when they are engaging in design projects in engineering classrooms. As educators, we can benchmark whether and how are students engage in question asking, and we can then scaffold question asking behaviors if we see that it is a skill they need help building. Our observations of expert question asking behaviors give us some guidance already about where students may need some help. To illustrate, we could anticipate that students may need some prompting to ensure that they engage in asking enough convergent questions, such as DANF and DAR questions at the beginning of a design process to adequately scope out a project before diving into modeling activities. We also want to encourage students to ask questions throughout the design process, not just in the beginning. In addition, we observed that each type of expert asked questions consistent with their expertise. We could anticipate that engineering students would benefit from being prompted to ensure that they are either working with people with other areas of expertise or at least asking questions from many different perspectives. We could also anticipate that students might not naturally ask the decreasing ambiguity reasoning (DAR) questions that we did not see much of in this analysis with data from a lab-based setting. In classroom-based settings, like lab-based settings, it can be difficult to incorporate this kind of questioning – however examples that could be scaffolded for students include activities such as physical prototyping, simulations or user research.

Perhaps the most counter-intuitive kinds of questions for students would be those that are divergent - or increase the ambiguity of a situation (i.e., IA questions and sub-code questions). We are used to questions helping us to bound or constrain a problem, not broaden the boundaries. The experts in this sample provide compelling examples of how questions can be used to challenge the "rules" of a problem, tackle a problem by making it more complex and adding constraints, and to think outside the boundaries that are "given". This kind of divergent thinking that manages ambiguity is what we are hoping we can teach engineering students, so they will be prepared for the kinds of design problem solving they will encounter when they graduate.

5. Limitations

In this paper, we present findings of question-asking behavior in design by comparing three domain experts to three non-domain experts. Since the study was conducted in a laboratory environment and the data was collected using verbal protocol analysis, there are some limitations. Methodologically, understanding questioning behavior in design in such environments excludes the effects of social and situational factors on the design process. For example, in the results very few *decreasing ambiguity reasoning* (DAR) questions were posed. This is due to the experimental setting and the nature of DAR questions. Also, in Elizabeth's case, she had not initially understood that she could ask questions of the experiment administrator, as a result this could have altered her question-asking behavior.

In terms of the number of participants, with only 6 participants, our findings can only be generalizable to our sample. From the results, we see that these three engineering design experts predominantly pose questions related to technical aspects of the design situation, thus for the most part working from their technical expertise. A closer examination of the kinds of inquiry considered across different disciplines and approaches driven by evolving questions of modeling theory and techniques, increasingly divergent from the contexts of actual practice, may provide deeper insights about how different modes of thinking manifest in design inquiry and which ones fall outside the boundaries of domain knowledge and technical rationality. In addition, by comparing the ways in which experts in different disciplines do questioning, we are able to understand how domain experts operationalize their repertoires of knowledge, experiences and strategies in unfamiliar design situations in order to develop accounts of their *reflection-in*-action when managing ambiguity so it may inform our teaching and help students engage in different modes of thinking where they ask questions from different perspectives in order to push beyond the given boundaries of a design problem.

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Appendix A: Playground Protocol

PROBLEM ONE: DESIGNING A PLAYGROUND

You live in a mid-size city. A city resident has recently donated a corner lot for a playground. You are an engineer who lives in the neighborhood. You have been asked by the city to design equipment for the playground.

You estimate that the children who usually use the equipment will range in age from 1 to 10 years. However, occasionally some adults will also use this equipment. From the amount of space you have in the park, you estimate that you should design equipment to keep 12 children busy at any one time. You would also like to have at least three different types of activities. for the children. The equipment must:

- be safe for the children,
- remain outside all year long,
- not cost too much,
- comply with the Americans for Disabilities Act, so handicapped children will be able to play also.

The neighborhood does not have the time or money to buy ready-made equipment pieces. Your design should use material that is available at any hardware or lumber store. The equipment must be constructed in under 2 months.

Please explain your solution as clearly and completely as possible. From your solution, someone should be able to build your playground without any questions. The administrator has more information and tools to help you address this problem if you need them. You must be specific in your requests. For example, if you would like a diagram of the corner lot for the playground equipment, you may ask for it now. If you think of any more information you need as you solve the problem, please ask.

Remember, you have approximately 3 hours to develop a complete solution. The administrator will inform you about how much time is left as you work.

LOT APPEARANCE

The current lot is perfectly flat. There are no trees on the lot. The lot is covered with grass and weeds. There is a 9 ft. fence surrounding the lot, and two gates. One gate faces 2nd Avenue and the other faces Pine Street.

Appendix B: Engineering Design Expert and Playground Expert Profiles

Eldon: Eldon starts the design process by asking questions to understand the context and restrictions he may have. He asks for the layout, the Americans with Disabilities Act (ADA) guidelines, location of the city and budget. He also focuses on understanding if there are city ordinances or zoning requirements that should be met. He asks about power, water, and other utility lines that might cause problems when digging to construct the playground. Once he realizes there is a nine-foot fence, he asks if there is any information about the fence.

For example, he questions "is it made out of wood, does it need to stay there, is it in good condition?" He seems to ask these questions to access his consider the budget provided in the problem statement. He also asks a series of questions to confirm whether the restriction is the money (to buy ready-made materials) or if it is just a restriction placed on this design exercise. Finally, he asks if he has to buy things from the hardware store or if he can get free tires from a junkyard. He details what his process will be, [line 145] to put together a rough design, work out budgetary constraints and amend appropriately. He asks about the volunteers he will have; in which he is told he can assume anything on volunteers. From this response, he decides to list the assumptions he is making. Finally, he asks about load bearing capacity, realizes he does not know how to calculate that as an electrical engineer and decides to assume that he can get that information from the hardware store. At this point, he reviews where he is in his design process and decides to start laying out the playground. He continues to review his design process throughout the three hours. Eldon restates his design process, acknowledging it is a rough design for costing purposes and decides to add in 10% for cost overrun. He tries to create a modular design to have different teams of volunteers working at the same time. Reviewing the design requirements that he has to meet, he starts to look at the scaled down layout of the lot. He starts listing the things he is adding to the playground such as a climbing wall, ladder, sandbox, tire swing, and platforms. He then wonders if there is an approval process and if someone will check his work. After assuming that there is, he will have to take the role of designer and reviewer. He mentions that he needs to make sure he knows whether he is designing a 1-thousand-dollar playground or 10-thousand-dollar playground.

He looks for pinch points, makes sure there is a play space that meets ADA requirements, that the material is appropriate for the climate, and that 12 children will be able to use the playground at the same time. At the end of the design session Eldon reviews and approves his design.

Eric: Eric's design process entails listing the knows and/or requirements, the constraints, and then coming up with options and considering solutions by basing it on those that fit a criterion. In doing so, he continually generates options and his process checks are articulated as questions to himself; for example, "What else do I need?" (Line 85). He starts gathering information about wood and metal materials, then playground equipment like swings and chains. He then confirms what information he has then plans to start from the ground up (Line 127) and continues working things back (Line 128). Starting with the overall layout, he considers choices for the loose material surface since it is the easiest to calculate while coming up with better ideas as far as what kind of equipment to have. While considering the overall layout, Eric becomes preoccupied with visualizing "how big 75 feet is" (Line 139). While he is able to make rough estimates for determining the area of the lot, he expresses concerns related to access and handicapped people (Line 202-203). The "handicapped issue" (Line 202) and visualizing the playground area occupies most of Eric's time, where he asks for examples of playgrounds (Line 249). His time is also spent on generating ideas related to playground equipment and consolidating the playground equipment into one project. As he considers particular playground equipment, he gathers information such as the dimensions, makes "roughed up" (Line 514) sketches and calculations, ensures he has accounted for the "Americans Disabilities Act. General safety regulations" (Line 553), and then determines the costs. In "thinking too much about the whole plan of what's it going to look like" (Line 694-695), and getting "hung up on the whole accessibility issue" (Line 696), Eric successfully conceptualizes his design through planning but runs out of time determining how to tie everything together (Line 649) and mapping out the costs (Line 651).

Elizabeth: Her approach to the playground design exercise can be separated into three main phases: ideation of playground layout and types of equipment, designing each piece of individual equipment, and budgeting for materials. During her process, she frequently references to the problem statement to assess the viability of her solution Whenever she receives new information she modifies her design accordingly [example of this]. Elizabeth begins by coming up with ideas for the types of playground equipment that would satisfy the problem requirements, focusing on equipment that would appeal to a diverse set of ages (Line 20) as well as some equipment that children in wheelchairs could engage with (Line 61). She frequently references the problem statement, specifically the need to potentially engage 12 children at once (Line 74). Once she has come up with ideas for what equipment should be included in the playground, she moves on to laying out the area and making sure it fits in the 75'x75' plot of land. At this point, she asks about the budget (Line 91), and modifies her design to forgo the bathrooms and water fountains she had previously included. The budget continues to be the area of greatest consideration for Elizabeth, and she frequently proposes ways to address its size, such as garage sales or building in phases [example of this]. When she moves on to designing each individual piece of equipment, she asks for information that will help her complete the immediate problem, such as material costs, ADA guidelines, and safety guidelines. In choosing materials, Elizabeth references knowledge about what things are available at hardware stores. She creates drawings to assist her in calculations of the material sizes, and notably attempts to use the same materials across difference pieces of equipment to cut down on costs, even if it would cause her to redesign portions of her playground. She makes assumptions about the appropriate sizes for the equipment she is designing. The majority of her time spent on this task is devoted to calculations and pricing materials, with her talking through the calculations as she does them. She finishes the task with a list of what materials to purchase and designs that would guide a potential playground constructor.

Playground Design Expert Narratives

Perry: Perry begins his process by trying to understand the context in which this playground is being created. He asks for a lot of information about the surrounding community, such as the demographics of the families (Line 22), community support for the project, the relationship with the city, neighborhood opinions on equipment, etc. He often asks for information the administrator does not have and is told to make assumptions. This leads to him creating a scenario beyond the constraints of the problem statement. He states the playground as the mayor's "pet project" and states the playground will volunteers. Perry begins creating the design by attempting to understand and design the "flow" of the park, drawing many visual aids to assist in understanding the park's size and perspective. He remarks on the amount of the budget is and comes up with many ideas to work with the constraint, including relationships with the mayor's office, the city bus service (Line 295), county landscapers (Line 299), and various members of the community such as blacksmiths and artists. He also attempts to minimize purchases by using materials that would be available for free, such as the dirt that is already part of the park or mulch from a friend who has too much of it. The resulting park design has an emphasized landscaping, where dirt is moved to create a hill and trees are planted around the outer perimeter (Line 385). Perry frequently references his knowledge as a playground designer, particularly with regard to the budget, park size, etc. He also describes what he would do for a project like this if he wasn't in a lab setting (insert line). This includes interviews with community members, spending time on the project site, and spending more time on drawings. He assumes that the community will come together for the creation of this playground, and assigns himself tasks for the playground's realization (such as "spraying out paths" (Line 337)). Much of his time is spent on the drawings and describing the park scenario and creates diagrams for a swing set in addition to his landscaping and perspective drawings.

Patrick: Patrick's approach begins with gathering information on the Americans for Disabilities Act (ADA) and general information related to the surroundings of the lot including lot topography. Next, he considers the users, in particular children and later parents, and then the structural and material aspects, such as the borders of the playground in relation to the entrance of the lot and surface materials. While generating ideas about how the elevated area interacts with the fence, he checks his process based on the sketch and scale used. Working from the borders in and evaluating his propositions, he moves to the next aspect of the playground, that is, the fill material and then on to playground equipment. While working on a particular playground equipment, Patrick considers different activities for different users. For example, he divides the play areas into two sections: one for younger children and children with disabilities where he designs low height climbing and some upper body activities, and another for older children with more challenging events. As he considers particular playground equipment, Patrick zooms in and when moving to the next playground equipment, he first zooms out by considering the overall layout and then zooms back in to the next playground equipment. Once he has included all the activities, he then works with his sketch and models each piece of equipment systematically. While he does, express concern related to the budget and the cost of the kid tiles, he comes up with a feasible solution that addresses his initial focus on surfaces that are accessible for individuals with disabilities. He is also concerned about access particularly for children with disabilities. This drives his design of the playground. Patrick draws on his professional knowledge related to playground safety where he requests information on CPSC requirements (Line 24), fall zone areas (Line 25), kinds of surfacing needs (Line 25), and "acceptability of various surface materials, table of maximum safe falling distances (Line 30). Based on the information he is provided with, he intentionally assumes that the various heights of the equipment are accessible surfaces ("from my experience, I'm assuming that these heights are accessible surfaces such as platforms or any walking surface", Line 32). Based on the available materials and his knowledge of the Americans with Disabilities Act, from the onset he does not recommend soft materials and instead proposes to use rubber surfacing. With experience designing playgrounds for the Americans with Disabilities Act, Patrick considers play activities that are designated areas with different users in mind. Foregrounding safety on a playground, Patrick uses his professional knowledge to hedge about safety setbacks, thus demonstrating the limits of his knowledge while overcoming this limitation by requesting CPSC or IPEMA information and using his professional knowledge.

Phil: Phil begins by questioning the prompt, as it did not make sense to him that the community does not have the money to buy ready-made materials (an intentional constraint to get participants to do design work). Making your own playground equipment, in his experience, takes more time and potentially costs more money. He then proceeds to get a better understanding of where this park is located. What are the community demographics, is it in the United States, is it a public or private park? He quickly jumps to the conclusion that he would not agree to do this in real life as it involves too many risks and liability issues, given that it is in the U.S. He then considers an adventure playground, which requires fewer physical structures and brainstorms potential ways to get more funding.

His expertise keeps him concerned about the feasibility, as he states that playgrounds are usually about a thousand dollars per child it serves and mentions that ADA surfacing is costly. He reframes the setting again and considers using the $3800 to hire someone to advocate for the park, or for a clean-up project and finally considers making it a water park, eliminating the need for active play.

He decides that trying to convince the community to do a community garden might be the best way to go. At this point the administrator gives him the option to finish the design prompt there or to try to design in a different location. He decides to build in a tsunami relief zone and asks about there being free materials or donations in kind. Now that he is in a third world country he will not have to worry about ADA. He brainstorms possible playground equipment, considers an adventure playground again, and then decides that he will move forward with creating a drawing of an apparatus for the playground.

He begins thinking about the constraints and possibilities of being in a tsunami zone. He can use the sand from fall material but needs to consider wood rotting. He follows through with a swing design, taking into consideration the tools the volunteers will have to build the swings. As he works on the climbing gym, he checks for ADA accessibility, and other options that are fun but do not cost anything. He decides to create triangular decks instead of rectangular ones as believes this will cut the cost. At this point, he wants to check that the equipment fits within the lot, with appropriate clearance. He mentions that he would use CAD here. He adds a swing design and bench for parents and continues to model until he finishes.

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