Ibrahim Mohedas
Department of Mechanical Engineering,
University of Michigan,
2350 Hayward Street,
Ann Arbor, MI 48109
e-mail: imohedas@umich.edu

Shanna R. Daly
College of Engineering,
University of Michigan,
210 Gorguze Family Laboratory,
Ann Arbor, MI 48109
e-mail: srdaly@umich.edu

Kathleen H. Sienko[1]
Mem. ASME
Departments of Mechanical &
Biomedical Engineering,
University of Michigan,
2350 Hayward Street,
Ann Arbor, MI, 48109
e-mail: sienko@umich.edu

Requirements Development: Approaches and Behaviors of Novice Designers

Elicitation and development of product requirements are crucial aspects of front-end design and have significant impacts on future product success. This study sought to better understand how novice designers approach the development of product requirements during a front-end design task. Results showed that the stakeholder validity of participants' requirements and the level of tailoring of the requirements to the design context and stakeholders were highly correlated to the number of distinct information sources used and moderately correlated to participants' dependency on particular information sources. Furthermore, an in-depth exploration of participants' information gathering behavior during the design task elucidated specific strategies and processes that may explain why some participants were more successful than others.
[DOI: 10.1115/1.4030058]

Introduction

Activities associated with front-end design phases are characterized by their "fuzzy" nature, because they are ill-defined and have high levels of uncertainty [1]. Front-end design, defined as the phases of product development associated with problem definition, concept generation, and idea evaluation [2–4], presents unique challenges as the understanding of the problem and acceptable solutions co-evolve through iteration, and the nature of this iteration is often unstructured and has little formalization [5,6]. Case studies have demonstrated that the success of new products depends upon how well the front-end design phases are executed [3]. Studies have also shown that in many instances product failures are a result of critical decision errors made during the front-end design phases that could not be cost-effectively rectified later in the design process [2,7,8].

A key component of front-end design involves eliciting and developing product requirements. Product requirements are any function, constraint, or other property required for a designed artifact to meet the needs or wants of stakeholders; the requirements are translated into engineering specifications that are both quantifiable and measurable in order to guide engineering design processes [9,10]. The ambiguous and iterative process of developing product requirements and translating these requirements into engineering specifications is a challenging undertaking in design work [1]. To develop quality requirements, design experts have advocated the collection of information about end-users, stakeholders, and product-use environments from a variety of sources and using a variety of methods, such as interviews with end-users and other stakeholders, focus groups, surveys, customer complaints, sales data, and codes and standards [9,11,12]. Newer information gathering methods based on the philosophies of human-centered and participatory design include focus group brainstorming techniques, consensus-building workshops, the use of prototypes during elicitation, protocol analysis, and comprehensive design ethnographies [13–17]. These methods allow one to gain a better understanding of a product's stakeholders and its context of use in order to properly define product requirements.

Requirements elicitation methods involve extensive information processing. The necessity for a deep understanding of end-users and stakeholders requires designers to gather information from diverse sources, synthesize and analyze this information, and then apply it to make design decisions. The process represents a significant challenge for novice designers, as one must be prepared to use both technical and nontechnical skillsets [11,18–21]. Prior studies comparing novice and expert designers have emphasized this challenge and its effect on final design quality [22–25]. For example, a study of novices and experts performing a design task showed that novices spend less time gathering information and less time defining the scope of the design problem than experts [24]. It has also been shown that novice designers who spend more time refining the scope of their design problems tend to produce higher quality designs [26]. Our previous work has shown that novices understand the value and benefit of information gathering and synthesis while developing requirements; however, during execution they typically gather less information and perform less synthesis than originally planned [27]. In addition, while novices understand the benefits of incorporating stakeholders' input and field-based observations into the requirements development process, they encounter obstacles and use stakeholder interactions to gain only superficial benefits [21,28].

The development of product requirements and specifications can be characterized as a particularly open-ended and iterative information gathering process [29]. While some information processing work can be defined as "information transfer," where information is treated as an object and directly applied to the problem without further analysis or synthesis, developing product requirements more closely resembles "information use," where designers must incorporate the information gathered with their existing knowledge and apply it to the development of product requirements—a more cognitively demanding task [30]. Within this broader field of information gathering and application, and outside of the design context, studies have been conducted to understand how individuals identify needed information, seek out this information, and apply it during problem solving [31]. Research has shown that novices do not tend to assess the quality and/or validity of the information they obtain prior to applying it to their problems [32–35]. Similar results have been found for engineering students' use of internet sources through studies of design report bibliographies [36]. The importance of information gathering has also been demonstrated in practice, where companies in industries with higher uncertainty are more likely to rely

[1]Corresponding author.

Contributed by the Design Automation Committee of ASME for publication in the JOURNAL OF MECHANICAL DESIGN. Manuscript received September 29, 2014; final manuscript received February 22, 2015; published online May 19, 2015. Assoc. Editor: Carolyn Seepersad.

on external information, more frequently use all information sources available, and spend more time gathering information during problem solving processes [37]. While these studies have formed a solid foundation for further research on how information is gathered and used during engineering design, few studies have explicitly investigated the ways in which designers gather and use information during design processes.

Prior work has demonstrated that front-end design is critical to the success of new products, but detailed studies have not yet been conducted with respect to how novices perform requirements elicitation and development during front-end design. This study contributed knowledge to this topic by investigating novice designers who participated in a front-end design task.

Methods

Research Goals. The goals of this study were to investigate novice designers' information gathering behaviors and how the behaviors related to the development of product requirements. To achieve these goals, we used a mixed-methods approach; using quantitative methods, we examined how participants' information use correlated with assessments of their requirements, and using a case analysis approach, compared the behaviors of design task participants who varied in their levels of success during the development of product requirements. Similar to other studies investigating design processes [38–42], this study focused on collecting extensive data from a small sample of participants (rather than collecting limited data on a large sample) to obtain a deeper understanding of how the participants approached and executed the front-end design phases.

Our study focused on the use of information sources and information gathering behaviors and each focus was guided by corresponding research questions:

- Use of information sources: How do novice designers use information sources to develop product requirements? How do the ways novice designers use information sources relate to the quality of their requirements?
- Information gathering behaviors: What differences exist in information gathering behaviors between participants who develop requirements that receive high and low validity scores from stakeholders?

Participants. Eight students (five male and three female) in their fourth year of engineering (seven mechanical engineering students and one biomedical engineering student) volunteered as participants. Students were recruited via e-mail, using class e-mail lists from the fall and winter sections of the mechanical engineering capstone design course. Therefore, all students had completed or were in the final weeks of their capstone design course (i.e., had a minimum of one prior exposure to the front-end design process). Interested students completed a preselection questionnaire (Appendix A) designed to gather demographic and prior curricular, cocurricular, and extracurricular design experience information. The preselection questionnaire prompted students to estimate the level of experience with various design tools and design phases. We used a stratified random sample from the group of volunteers to achieve diversity in front-end design experience. Of the eight participants selected to participate, four had participated in cocurricular multidisciplinary design experiences (Participants 1, 4, 5, and 6), one participant had a minor outside of engineering (Participant 3, economics), two participants reported involvement in extracurricular design activities (Participants 3 and 4), and three participants reported having completed internships (Participants 2, 7, and 8). Participants were compensated $16 per hour.

Data Collection. To minimize the variability associated with studying front-end design, the same design task and access to information sources were given to all participants. The study was conducted in specific rooms on campus to facilitate detailed data collection of participant information gathering and use practices. The study was approved by the Institutional Review Board of the University of Michigan in accordance with the Helsinki Declaration and all participants gave informed consent.

The study spanned 8 h: 3 h of participant design activity (9:00 a.m.–12:00 p.m.), three and a half hours of design activity (1:00 p.m.–4:30 p.m.), and a 1-h break for lunch. After a brief explanation of the task (below) and a question and answer session, participants were free to schedule their time as desired.

Participants were presented with the following design task scenario (the term "user requirement" was used instead of "product requirement" to match the terminology used in the participants' capstone design course):

> You are currently working for a large toy company that specializes in toys for young children (0 to 10 years old). You've just received a job assignment from your boss. The executives have decided they would like to begin to develop toys that aid young children, between 1 and 5 years of age, in developing their cognitive abilities, specifically children's ability to explore and learn about cause and effect. You have been assigned the job of investigating this idea in order to understand the design problem, develop user requirements, and translate these user requirements into engineering specifications. You will be using standardized templates that your company has developed in order to document the user requirements and engineering specifications. In the future, you and a team will design the toy based precisely on the user requirements and engineering specifications you are developing, so be sure to include as much detail as possible. For now, your boss only wants to see the user requirements and engineering specifications.

The task was made intentionally broad in order to best simulate front-end design where the problem itself as well as the purpose, requirements, and features of the desired outcomes are not well defined. Furthermore, participants reported that they had not addressed this specific design task in prior curricular, cocurricular, or extracurricular activities. The design problem was formulated to be approachable by all participants and outside their domains of expertise, consistent with other design task studies [22,24,43]. Participants were given templates (Appendix B) to document each requirement, the priority level of the requirement, a justification for the requirement, and the information sources that contributed to the development of the requirement.

Each participant was assigned to a computer workstation to document the product requirements and engineering specifications and to access internet sources. Participants were also provided access to the following resources:

- Academic literature: electronic articles on childhood cognitive development
- Books: several books on children's cognitive development
- Guidelines: Consumer Products Safety Commission guidelines for determining proper age ranges for toys
- Observations[2]: children playing with various toys under parental supervision
- Stakeholder interviews[2]: various stakeholders including teachers, parents, a doctoral candidate studying cognition, an education expert (Ph.D.), and the director for a toy safety advocacy nonprofit
- Standards: ASTM F963-11 (Standard Consumer Safety Specification for Toy Safety) and ASTM F2729-12 (Standard Consumer Safety Specification for Constant Air Inflatable Play Devices for Home Use)
- Benchmarks: numerous toys for young children.

The data collection approach described below allowed us to track participants' activities throughout the day with minimal interference to their work. We collected various sources of data including overhead video camera footage of the computer workstation room, screenshots of participants' computers, computer surveillance data, audio-video recordings of stakeholder interviews,

[2]Observations were available 11:00 a.m.–12:00 p.m. and stakeholder interviews were available 10:00 a.m.–12:00 p.m. and 1:00 p.m.–3:40 p.m.

interview evaluations (by stakeholders), participant notebooks, post-task information use surveys, audio/video recording of a focus group discussion with stakeholders, requirements evaluations (by stakeholders), and audio recordings of post-task interviews with participants. This level of data collection allowed us to perform descriptive and exploratory quantitative analyses as well as in-depth qualitative analyses of participants' design deliverables and their strategies and behaviors during the design task [44].

Data Analysis. To answer our research questions, the following data were used: Product requirements developed by participants, stakeholder evaluations of requirements, overhead video camera footage, computer monitoring data, audio/video recordings of stakeholder interviews, and post-task interview recordings. The requirements developed by participants and the evaluations performed by stakeholders were used to address the first research question, and the remainder of the data were used to address the second research question. Analysis of the first research question included performing two assessments of participants' requirements and correlating them to descriptive measures of participant information use. Analysis of the second research question focused on identifying relationships and patterns in behavior across participants as they developed requirements.

Use of Information Sources. We investigated relationships between participants' use of information sources and both the stakeholder validity of their requirements and the degree to which requirements were tailored to the specific context and stakeholders of the design task. Several design texts describe criteria for assessing the quality of requirements. For example, Sommerville and Kotonya stated that requirements should be valid, consistent, complete, and accurate [45]. Garvin identified eight basic dimensions of quality including performance, reliability, durability, serviceability, conformance, perceived quality, aesthetics, and features [46]. Gause and Weinberg stressed the identification and reduction of ambiguity in requirement lists [47]. Requirements must also be solution independent [9]. Taking into account these criteria for requirements quality and the aim of our study (i.e., to characterize how novice designers use information sources to develop product requirements), we developed two metrics to assess the quality of requirements that heavily relied on participants' abilities to gather, synthesize, and apply stakeholder and context-based information: (1) stakeholder validity as defined by Sommerville and Kotonya and (2) the extent to which the requirements were tailored to the context of use and/or stakeholders through the application of Garvin's eight dimensions of quality.

Stakeholder validity is defined as the degree to which clients, end-users, and stakeholders confirm that product requirements accurately describe characteristics that would meet their needs and wants [48]. To measure stakeholder validity, the requirements developed by participants were presented to the stakeholders who had been available during the design task for interviews ($n = 7$). Stakeholders were given each participant's complete set of requirements and asked their level of agreement with two statements: (1) The requirements describe the important characteristics of a toy for young children and (2) the requirements describe the important characteristics of a toy aimed at aiding children (between 1 and 5 years of age) in developing their cognitive abilities, specifically learning about, and exploring cause and effect. A five-point Likert scale (strongly disagree, disagree, neither agree nor disagree, agree, and strongly agree) was provided to capture responses. The metric for stakeholder validity, V_i, was calculated using the following equation:

$$V_i = \frac{\sum_{j=1}^{7} \left[R_{ij} - \tilde{R}_j\right]}{7} \tag{1}$$

where i represents the participant's requirement list being evaluated and j represents the stakeholder who assessed the requirement list, R_{ij} is the rating (on the five-point Likert scale) given to participant i by stakeholder j, and $\tilde{R}_j$ is the median evaluation score given by stakeholder j (across all participants). The sum is divided by the total number of stakeholders (7) who evaluated requirements.

We also analyzed the extent to which participants' requirements were tailored to the specific context and stakeholders for whom they were designing. Participants who developed a larger number of these tailored requirements were deemed more successful in understanding the context and stakeholders for whom they were designing and applying their understanding to the development of product requirements. This assessment was accomplished by considering two of Garvin's eight dimensions of requirements: aesthetics and features [46]. These two dimensions encompass requirements that must be specifically tailored to the end-use context and the stakeholders who interact with the product, and therefore require a deeper understanding of the context of use and the stakeholders who will interact with the product. Features are "frequently used to customize or personalize a product to the customer's taste" while aesthetics represents the customer's response to how the product "looks, feels, sounds, tastes, and smells" [9,46]. Using this classification system, we calculated the number of requirements each participant developed that belonged to the first six dimensions as well as those that belonged to the last two (context and stakeholder specific) dimensions. Participants with a higher number of requirements pertaining to the dimensions of features and aesthetics (after being normalized by the total number of requirements generated by the participant) were deemed to have developed and applied a more thorough understanding of the product's context of use and the stakeholders who would interact with the product.

To examine the relationship between the above-mentioned metrics and how participants used information, we developed two metrics of information use. The first metric quantifies the diversity of information sources used by participants and the second characterizes participants' dependence on specific information sources while developing requirements. As part of the requirements template, participants were asked to cite the information sources that informed the requirements they developed. These information sources were subsequently classified into ten exhaustive categories (observations, interviews with parents/teachers, interviews with education experts (doctorate holder and doctoral candidate), interviews with the safety expert, academic literature, benchmarking, online resources, standards, given resources (e.g., books, guidelines), and the design task brief). These categories included all information sources cited by participants. The number of distinct information sources cited by each participant was then calculated, providing a measure for the level of diversity of the information sources participants used.

To quantify the level of dependence on specific information sources, we used the skew statistic for the distribution of information sources cited by participants (example distributions can be seen in Fig. 3(*b*)). This measure was calculated using Eq. (2), where n is the number of information source categories, x_i is the number of citations within the ith category, and $\bar{x}$ is the average number of citations per category. This measure of skew is insensitive to the ordering of information sources within the distribution.

$$\text{Skew} = \frac{\frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})^3}{\left[\frac{1}{n-1}\sum_{i=1}^{n}(x_i - \bar{x})^2\right]^{3/2}} \tag{2}$$

The higher the skew of a participant, the more dependent he/she was upon a small subset of information sources when developing requirements. Skew was normalized across participants. In order for more positive measures to be associated with less dependence on a small subset of information sources, the metric shown in Eq. (3) was used for the correlations performed in this study:

$$1 - \text{Skew}_{\text{norm}} \tag{3}$$

The two measures of information use were then correlated with the two metrics of requirements quality. Spearman's rank-order correlation was used to capture the relationships between the variables in accordance with the nonparametric data from the Likert surveys [49]. Using two-tailed significance tests, Spearman's correlation coefficient, ρ, and p-values were calculated for all metrics of interest.

Information Gathering Behaviors. The objective of the case analysis was to identify differences in information gathering behavior among participants whose requirements received high and low validity evaluations from stakeholders (Participants 2, 5, 6, and 7). Using a subset of the participants facilitated a detailed examination that included both quantitative metrics and qualitative coding, and thematic analysis [50–53]. The variety of data sources allowed for a comprehensive description to be generated with respect to how each participant spent his/her time during the design task and how he/she performed specific information gathering activities (such as stakeholder interviews). Individual timelines showing minute-by-minute activities during the design task elucidated how each participant spent his/her time [54]. Analysis of stakeholder interview transcripts was conducted by categorizing interview questions with an emergent coding system representing different topics of discussion (e.g., introductions, product requirements, and validation testing, etc.). The time spent on each topic during interviews was calculated to determine the focus of participants' efforts, leading to the identification of specific behaviors and strategies displayed by the participants. The post-task interview transcripts determined whether participants acknowledged these behaviors and strategies, and whether they were intentional or not.

Results and Discussion

The study results are described below in two sections: Use of Information Sources and Information Gathering Behaviors. First, we present the quantitative analysis results correlating participant information use behaviors with the quality of the requirements developed (answering our first research question). Second, we present the outcomes of the qualitative case analysis to compare the information gathering and use behavior of participants who developed high and low quality requirements (answering our second research question).

Use of Information Sources

Requirements Assessment. The first metric, participants' stakeholder validity scores, ranged from −0.33 to 0.50 for question 1 (the requirements describe the important characteristics of a toy for young children) and from −0.83 to 0.50 for question 2 (the requirements describe the important characteristics of a toy aimed at aiding children (between 1 and 5 yr of age) in developing their cognitive abilities, specifically learning about, and exploring cause and effect). The theoretical minimum for the stakeholder validity metric was −1 and the maximum was 1. Figure 1 shows that Participants 5 and 6 performed above average when assessed by this metric, with participant 6 performing markedly better than all other participants.

The second metric, the proportion of requirements that were tailored to the specific context and stakeholders of the design task, also revealed differences among the requirements developed by participants. Figure 2 shows that while all participants developed approximately the same number of basic requirements (requirements within the dimensions of performance, reliability, durability, serviceability, conformance, and perceived quality), Participants 4, 5, and 6 developed a larger quantity of requirements tailored to the specific context and stakeholders of the design task (requirements within the dimensions of features and aesthetics) than the other participants. The proportion of tailored requirements to the total number of requirements was used to establish correlations between information use and requirement assessment scores.

Assessing Information Use. Figure 3(*a*) shows the large variation with respect to how the eight participants used information to develop requirements. The number of distinct information sources cited by participants is displayed along the *y*-axis and the level of dependence upon particular information sources is displayed along the *x*-axis. Along the *y*-axis, higher values are associated with more diverse information use, and along the *x*-axis, higher values are associated with less dependence upon particular information sources. The large variation is most striking when comparing Participant 6, who used six distinct information sources and was not overly reliant upon any particular source, and Participant 1, who used only three distinct information sources and was highly reliant on one source (parent/teacher interviews) to develop requirements (Fig. 3(*b*)). The variations suggest that participants used different strategies with respect to how they applied information when developing requirements, but the variations do not conclusively show that participants gathered and/or synthesized information differently.

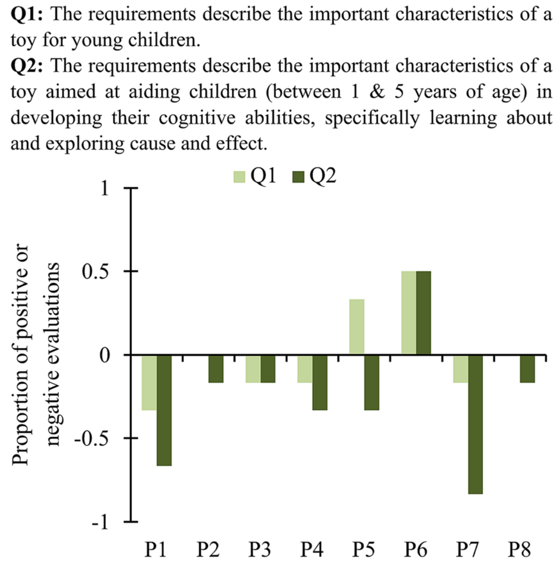

Fig. 1 Validity of participants' (P = participant) product requirements as evaluated by stakeholders

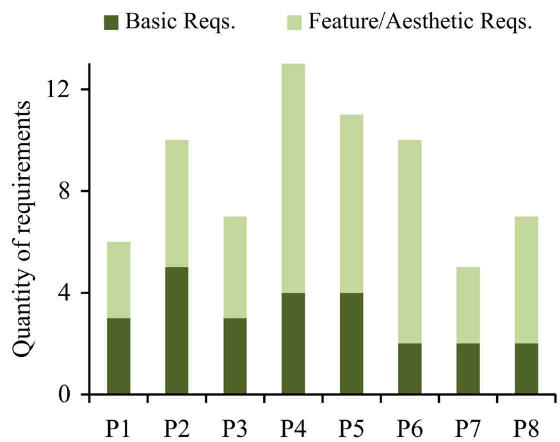

Fig. 2 Numbers of requirements developed by participants as classified using Garvin's first six dimensions (basic requirements) and those requirements that were context/stakeholder specific (feature/aesthetic requirements)

Effect of Information Diversity and Dependence on Requirements Assessment. A strong correlation ($\rho = 0.70$ and $p = 0.055$) was found between the stakeholder validity of participants' requirements and the number of distinct information sources used; participants who used many information sources produced requirements that received higher scores from stakeholders (Fig. 4(*a*)). Additionally, participants who used more diverse information sources developed more requirements tailored to the specific context and stakeholders of the design task as there was a strong correlation ($\rho = 0.83$ and $p = 0.011$) between the proportion of context-specific requirements developed by the participants and the number of distinct information sources used (Fig. 4(*b*)). Participants who were dependent on particular information sources were more likely to receive lower validity scores from stakeholders as there was a

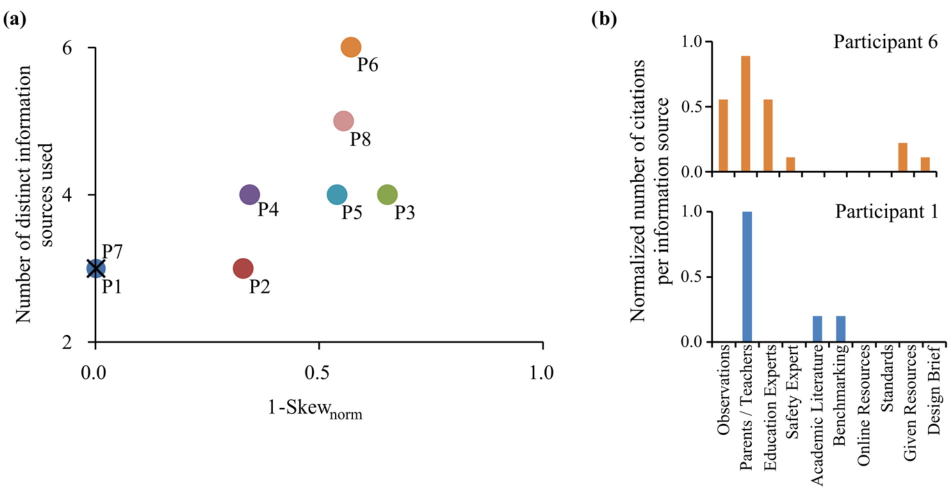

Fig. 3 Participants' use of diverse information sources (P = participant) and their dependence on particular information sources. Citations were normalized in Fig. 3(*b*) by dividing the total number of requirements (i.e., 1.0 indicates that the information source was cited in all of the participants' requirements).

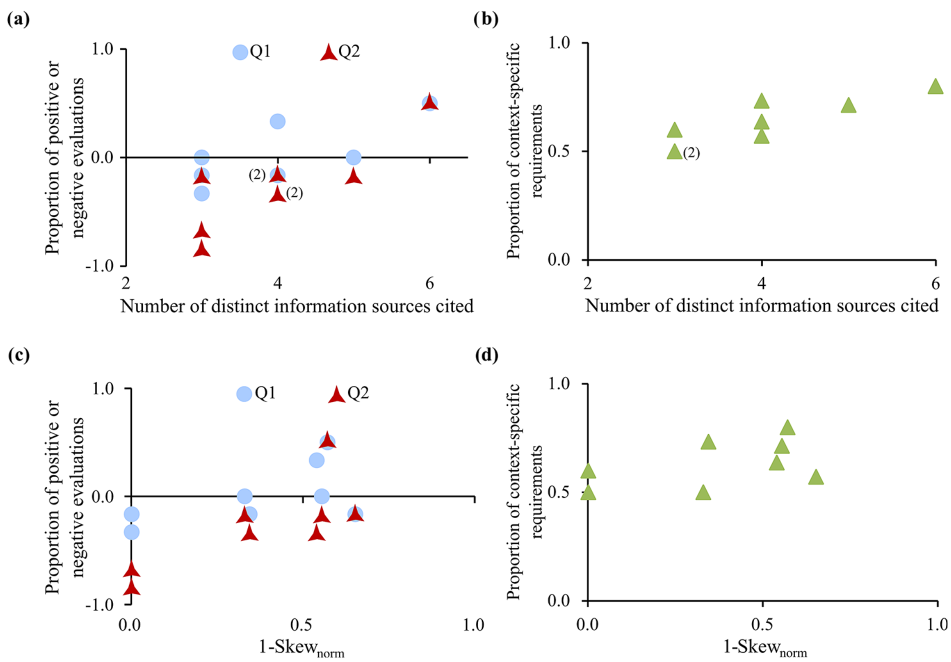

Fig. 4 Correlations between assessment of participants' requirements and the diversity of information sources (*a*) and (*b*); and their dependence on particular sources (*c*) and (*d*). Numbers in parentheses indicate overlapping data points (Q1 data points to the left of symbols and Q2 data points to the right of data points).

strong correlation ($\rho = 0.79$ and $p = 0.020$) between the stakeholder validity metric and the information dependence metric (Fig. 4(*c*)). There was a nonsignificant weak correlation ($\rho = 0.48$ and $p = 0.233$, Fig. 4(*d*)) between the proportion of requirements specifically tailored to the context and stakeholders of the design task and the participants' dependence upon particular information sources.

The results suggest that use of diverse information sources and avoiding dependence on particular information sources are important factors for developing requirements that meet the expectations of stakeholders and are tailored to a product's context of use and stakeholders. The findings are consistent with common engineering texts that recommend consulting a variety of information sources during requirements development and confirming the requirements via multiple sources, rather than depending upon a small number of sources [9,11,12,45]. Our findings reinforce this concept by showing that diverse sources of information are critical to the development of quality product requirements.

Information Gathering Behaviors. Below we present the analysis of the behaviors and approaches of Participants 6 and 8 (high stakeholder validity assessments), and Participants 7 and 2 (low stakeholder validity assessments) to understand why some participants excelled and others struggled during the development of product requirements.

Case 1: Participant 7. Participant 7 scored lowest in the evaluation of requirements by stakeholders and developed only five requirements during the design task (the average for all participants was eight), three of which were tailored to the context and stakeholders of the design task (the average was 4.87). Participant 7 also used the fewest number of distinct information sources and was the most dependent on particular information sources to develop requirements.

The timelines shown in Fig. 5 display the activities of Participants 6 and 7 based on the minute-by-minute analysis. Time is shown from left to right (beginning to end of the design task) and a block is placed in line with the participant's activity at the time indicated on the *x*-axis. Participant 7's use of time and handwritten notes shows extensive time spent in performing data collection (Fig. 5(*a*)). However, Participant 7 did not begin to document requirements until the final hour of the design task, which was markedly different from the higher performing participants, such as Participant 6, who began documenting requirements roughly two and a half hours prior to the end of the design task (Fig. 5(*b*)). Participant 7's approach left little time to properly analyze the information gathered and apply it to his requirements and may have led to the lower validity scores he received.

Participant 7's time management approach was also evident in his handwritten notes that only captured information gathering activities and showed no attempt to analyze the information gathered. During the post-task interview, Participant 7 described how he spent time during the day:

> "…defining all of my user… requirements and engineering specs, that was a full out blitz from somewhere around 3:30ish to right at 4:00 and …so up until that point it was just all research based."

Participant 7's efforts to collect as much information as possible without anticipating the amount of time needed to synthesize or incorporate the information into the requirements likely prevented him from effectively leveraging the information collected, and may have led to receiving low stakeholder validity scores for his requirements.

Case II: Participant 2. Participant 2 performed just below average with respect to the stakeholder validity scores for her requirements. Only half of the requirements developed by Participant 2 were tailored specifically to the context and stakeholders of the design task; participants with above average stakeholder validity scores had approximately 70% of their requirements tailored specifically to the context and stakeholders of the design task. Participant 2 only used three distinct information sources, but was not overly dependent on any one of them. Unlike Participant 7, Participant 2 began documenting requirements early and continued until the end of the design task. However, Participant 2 may have been overly reliant on online sources to complete the task. Figure 6 compares the time spent during the interactive design task by Participants 2 and 5. Compared to Participant 2, Participant 5 consulted a broader range of information sources and referred to them more uniformly. Participant 2 spent close to 90 min consulting online sources, which was more than twice as much time spent compared with any other Participant assessed. During the post-task interview, Participant 2 discussed this aspect of her approach:

> Interviewer: "What would you say was the most important resource during the day that you used?"
>
> Participant 2: "Probably the internet … because it's helpful talking to people, but…they're very subjective…to what they've just been through, …and it's not … a general sample."

Participant 2 associated online research with the acquisition of more "generalizable" knowledge and associated interviews with a more anecdotal form of knowledge acquisition, which possibly explains why she relied more on online sources and did not use other sources as much as other participants. Participant 2's perception of interview methods for requirements development may have hindered her from effectively leveraging this information source during the design task.

Case III: Participant 5. Participant 5 performed above average with respect to both requirement quality metrics. Participant 5 used the six types of information sources available without becoming dependent on any one source as shown in Fig. 6. Participant 5 also displayed more advanced information gathering and use behavior with respect to interviews and observations. For example, Participant 5 developed a questionnaire for parents to complete during the observation session to better understand their perspectives. He then used the questionnaire to structure interviews with stakeholders and modified it as needed [47]. This approach allowed Participant 5's interviews to focus more on the requirements; whereas other participants spent more time discussing background issues with stakeholders versus talking directly about product requirements. Participant 5 also displayed more advanced design process knowledge by narrowing the focus of the design task based upon the information he collected [24,26,55]. The original task indicated that the toy should be targeted to children from ages one to five; however, Participant 5 narrowed the focus to ages one to three given that most of the cognitive development for this specific attribute (cause and effect learning) occurs during these years. Other participants, such as Participant 2, mentioned the difficulty of developing requirements for such a large age range, but did not recognize the opportunity to redefine the problem more appropriately.

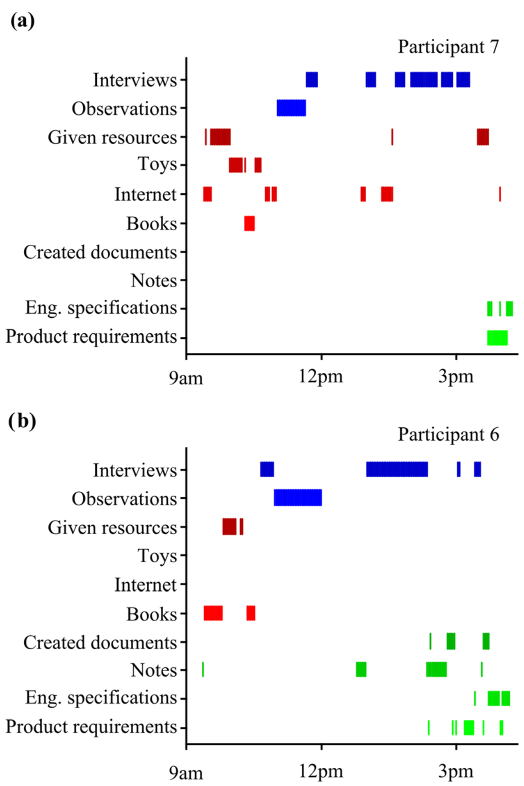

Fig. 5 Timeline showing time use during the interactive design task for Participants 6 and 7

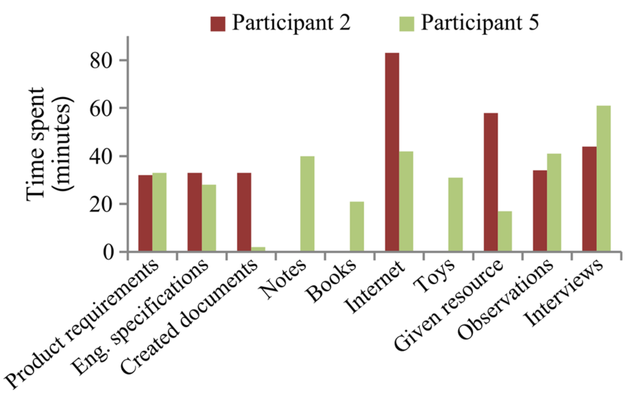

Fig. 6 Summary of Participants' 2 and 5 time use during the course of the interactive design task

Case IV: Participant 6. The requirements developed by Participant 6 received the highest scores from stakeholders. Participant 6 cited the most diverse set of information sources and did not depend on any particular information sources. During the design task, Participant 6 spoke with more stakeholders than any other participant, holding seven interview sessions with stakeholders (four were conducted as focus-group style interviews with two to three stakeholders each). Additionally, Fig. 7 shows that Participant 6 balanced her time during interviews with stakeholders and discussed a broad range of topics. The balanced interviews may have allowed Participant 6 to develop a more holistic understanding of the stakeholders interviewed.

Participant 6 was also one of only two participants to present stakeholders with a preliminary version of the requirements developed. The direct feedback obtained from the stakeholders about the requirements displayed Participant 6's ability to employ a more participatory approach to stakeholder interaction during the design process [56]. During the post-task interview, Participant 6 mentioned the benefit of being able to interview parents while their children were playing in the same room.

> "… I was glad that I was able to … interview parents during [the observation session], even though it was informally, because they were … in their setting … with their child … playing with them so the things they said were just more … candid and they were … in the mindset of … their kids playing with the toy"

Interviewing parents during the observation session allowed Participant 6 to ask questions based on the children's real-time behaviors. Unlike a neutral environment (an interview room), the natural environment likely aided the parents by providing them with contextual cues that could help inform their answers [57,58].

The case analyses of Participants 2, 5, 6, and 7 showed that participants who developed requirements that were scored more highly by stakeholders (Participants 5 and 6) also exhibited more sophisticated information gathering and requirements development strategies. We observed that Participants 5 and 6 used their observation sessions to talk to the parents in a more natural environment, developed surveys to provide structure to their interviews, performed more balanced information gathering (in general throughout the design task and specifically during interviews with stakeholders), and sought feedback from stakeholders about requirements [47,56–58].

Previous studies have shown that time spent gathering information impacts design outcomes. In this work, we found that the strategies participants used when gathering information also had an impact on outcome quality [26]. For example, Participants 6 and 7 used similar information sources and spent similar amounts of time gathering information, but received markedly different validity scores from stakeholders. From our findings, we conclude that simply gathering an extensive amount of information while developing requirements does not yield high quality requirements.

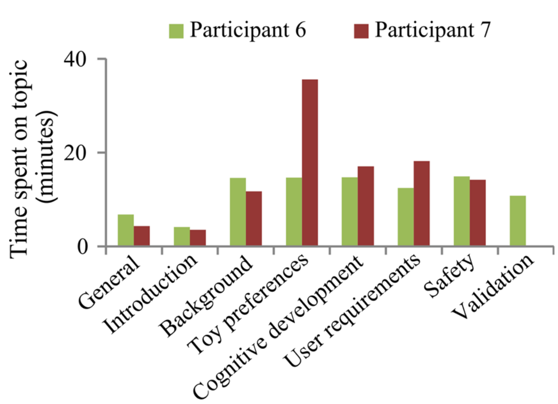

Fig. 7 Time spent discussing specific topics by Participants 6 and 7 during interviews with stakeholders

Instead, novice designers need to gather information effectively and then synthesize, analyze, and apply it appropriately.

Participants 5 and 6 displayed sophisticated information gathering techniques and were able to transfer their data into high quality requirements. Participants 2 and 7, however, were less successful, because they were unable to translate the data collected during the design task into the development of appropriate product requirements. Our prior studies have found similar trends, where engineering students in capstone courses encounter difficulties while attempting to incorporate diverse information sources into the development of product requirements [21,27].

Limitations. The development of a structured design task that simulated aspects of front-end design allowed us to understand the processes by which novice designers gather and use information during the development of product requirements. However, there were limitations associated with the format of the design task. The group nature of the study wherein all participants performed the same design task simultaneously could have caused some participants to perform observations or stakeholder interviews simply because they noted that other participants were doing so, and they might not otherwise have used these sources. Also, allowing the participants to schedule interviews and focus group appointments with stakeholders as desired possibly benefited those who conducted their interviews later in the day, because earlier interviews could have "primed" the stakeholders. Additionally, we did not control for the effect of performance in the capstone design course or cumulative grade point average; however, a retrospective analysis of participants' grades in the capstone design course indicated that all of the participants were strong design students (grades ranged from B+ to A).

This study focused on collecting an extensive amount of data on a relatively small number of study participants. While the outcomes are not generalizable, the goal was transferability, meaning rich detail is collected and reported so that other researchers can apply and translate the findings into their own contexts [59].

Conclusions

This study sought to better understand the processes used by novice designers to gather and use information during the development of product requirements. Participants with higher stakeholder validity scores and a larger proportion of requirements tailored specifically to the context and stakeholders of the design task cited the most diverse set of information sources and did not rely upon a singular (or small subset of) information source(s) to develop requirements. We suggest that a curriculum for teaching requirements development should encourage novice designers to gather diverse information and synthesize the information before developing requirements. Requiring a minimum number of diverse information sources as justifications for requirements and ensuring that each requirement is supported by multiple information sources may provide the necessary incentives until novices develop a deeper understanding of the benefits of such information gathering and use strategies. In addition, the literature on information gathering and use has demonstrated that novices tend to struggle with complex information processing tasks; therefore, novice designers may need instruction on general strategies for gathering and synthesizing diverse information.

The case analyses identified novice behaviors that could be countered with targeted pedagogy. For example, dependence on internet sources while ignoring information sources such as interviews with stakeholders or observations may be prevented by fully defining the breadth of information sources and methods for gathering information before novices begin to develop requirements. Demonstrating the iterative process of requirements development could prevent novices from treating it as a one-time activity, where information gathering fully precedes development of requirements. Furthermore, often in capstone design courses, the development of product requirements is performed on an accelerated timeline. Design course curriculum could provide opportunities for additional time for this design phase.

The development of requirements specifically targeted to a product's context of use and to its stakeholders is key to the success of human-centered design processes [60] that focus on the actual stakeholders who will interact with the product. This study demonstrated that gathering information from diverse sources is a useful strategy for identifying context- and stakeholder-specific requirements.

Acknowledgment

The study team thanks Kristen Ydoate and Linh Huynh for their help developing and executing the interactive design task and Gabrielle Fantich for her help transcribing the interview recordings. The study team also thanks the eight undergraduate design students who volunteered to participate in the study. The study team would like to thank Steve Skerlos and James Holloway for their data analysis suggestions. The study team also thanks Ann Stewart for her assistance with editing. This work was supported by the University of Michigan's Rackham Merit Fellows program, the National Science Foundation's Graduate Research Fellowship program, the National Science Foundation's Research Initiation Grants in Engineering Education (RIGEE 1340459), the National Science Foundation's CAREER program (RAPD-0846471), and the University of Michigan Center for Research on Learning and Teaching's Investigating Student Learning Grant.

Appendix A

Below is the pre-selection questionnaire participants completed during recruitment.

First Name:	Last Name:
Email:	Major/Minor:
Semester when ME450 (capstone design) was taken:	Current Year of Study:
List all courses you have taken during your undergraduate career that have had a design component/project. Instructions: Give the name (e.g. ME450), the year and semester you took the course (e.g. Fall 2013), and a one sentence description of the design component.	
List all co-curricular and extracurricular activities you have participated in during your undergraduate career that have had a design component/project. Instructions: give the activity name (e.g. XYZ), the time span you participated in the activity (e.g. Fall 2013 – Summer 2013 or Winter 2012 – present), and a one sentence description of the design component.	
List all internships, work experience, or research projects during your undergraduate career that have had a design component/project. Instructions: Give the experience name (e.g. internship with XYZ), the time span you participated in the activity (e.g. Fall 2013 – Summer 2013 or Winter 2012 – present), and a one sentence description of the design component.	
Based on all the design experiences above how much experience do you have with the following design tools, methodologies, or information sources (four options available: no, little, some, and substantialexperience):	

	Experience					Experience			
Design tool, method, or information source	No	Little	Some	Substantial	Design tool, method, or information source	No	Little	Some	Substantial
3D Printing					Focus Groups				
6-3-5 Method					Usability Tests				
C-Sketch					Gantt Chart				
Benchmarking					Pugh Chart				
Sketching					Market Analysis				
Brainstorming					Design Heuristics				
CAD Programs					Patent Search				
Cost/Benefit Analysis					Life Cycle Analysis				
Quality Function Deployment					Functional Decomposition				
Design of Experiments					Reverse Engineering				
Black Box Diagrams					Modeling and/or Simulation				
End-User Observations					Surveys of Stakeholders				
Academic Literature					Finite Element Analysis				
User Requirement Elicitation					Engineering Specification Development				

Appendix B

User Requirement Template and Instructions.

Instructions: Below is the template used by your company to organize the user requirements developed for all the toys they produce. Fill out the sections using the following format:

Column 1: Priority level—you must rank the user requirements in order of most important (ranked as 1) to least important. User requirements with the same level of importance may have the same priority level designation.

Column 2: User requirement—provide a clear description of the user requirement that you have developed.

Column 3: Justification—in the form of full sentences explain why the user requirement was included.

Column 4: User requirement information sources—list the information source(s) that contributed to the user requirement developed.

Priority Level	User Requirement	Justification	User Requirement Information Sources
**Add as many rows as needed			

Engineering Specification Template and Instructions.

Instructions: Below is the template used by your company to organize the engineering specifications developed for all the toys they produce. Fill out the sections using the following format:

Column 1: User requirement—state the user requirement for which the engineering specification was developed.

Column 2: Engineering specification(s)—state the engineering specification(s) that was developed, multiple engineering specifications can be used for a single requirement if needed.

Column 3: Justification—indicate why this engineering specification is needed to satisfy the user requirement.

Column 4: Engineering specification information sources—indicate what information was used to develop the specification, provide as much detail as possible so that future design engineers would know exactly what information went into the engineering specification.

User Requirement	Engineering Specification	Justification	Engineering Specification Information Sources
**Add as many rows as needed			

References

[1] Gupta, A. K., and Wilemon, D. L., 1990, "Accelerating the Development of Technology-Based New Products," Calif. Manage. Rev., **32**(2), pp. 24–44.

[2] Cooper, R. G., 1988, "Predevelopment Activities Determine New Product Success," Ind. Mark. Manage., **17**(3), pp. 237–247.

[3] Khurana, A., and Rosenthal, S. R., 1998, "Towards Holistic 'Front Ends' in New Product Development," J. Prod. Innovation Manage., **15**(1), pp. 57–74.

[4] Kim, J., and Wilemon, D., 2002, "Focusing the Fuzzy Front-End in New Product Development," R&D Manage., **32**(4), pp. 269–279.

[5] Murphy, S. A., and Kumar, V., 1997, "The Front End of New Product Development: A Canadian Survey," R&D Manage., **27**(1), pp. 5–15.

[6] Dorst, K., and Cross, N., 2001, "Creativity in the Design Process: Co-Evolution of Problem–Solution," Des. Stud., **22**(5), pp. 425–437.

[7] McGuinness, N. W., and Conway, H. A., 1989, "Managing the Search for New Product Concepts: A Strategic Approach," R&D Manage., **19**(4), pp. 297–308.

[8] Davis, A. M., 1993, *Software Requirements: Objects, Functions, and States*, 2nd ed., Prentice Hall, Upper Saddle River, NJ.

[9] Dieter, G. E., 2012, "Problem Definition and Need Identification," *Engineering Design*, 5th ed., McGraw-Hill, New York, pp. 75–115.

[10] Pahl, G., Beitz, W., Feldhusen, J., and Grote, K. H., 2006, *Engineering Design: A Systematic Approach*, 3rd ed., Springer, London, UK.

[11] Nuseibeh, B., and Easterbrook, S., 2000, "Requirements Engineering: A Roadmap," Conference on the Future of Software Engineering, ACM, Limerick, Ireland, June 4–11, pp. 35–46.

[12] Dym, C. L., Little, P., and Orwin, E., 2013, *Engineering Design: A Project-Based Introduction*, 4th ed., John Wiley & Sons, Hoboken, NJ.

[13] Maiden, N., and Rugg, G., 1996, "ACRE: Selecting Methods For Requirements Acquisition," Software Eng. J., **11**(3), pp. 183–192.

[14] Davis, A. M., 1992, "Operational Prototyping: A New Development Approach," IEEE Software, **9**(5), pp. 70–78.

[15] Goguen, J. A., and Linde, C., 1993, "Techniques for Requirements Elicitation," 1st IEEE International Symposium on Requirements Engineering (RE'93), IEEE, San Diego, CA, Jan. 4–6, pp. 152–164.

[16] Sommerville, I., Rodden, T., Sawyer, P., Bentley, R., and Twidale, M., 1993, "Integrating Ethnography into the Requirements Engineering Process," 1st IEEE International Symposium on Requirements Engineering (RE'93), IEEE, San Diego, CA, Jan. 4–6, pp. 165–173.

[17] Mohedas, I., Daly, S. R., and Sienko, K. H., 2015, "Applying Design Ethnography: A Case Example of a Medical Device in a Low-Resource Setting," International Conference on Engineering Design.

[18] Macaulay, L., and Mylopoulos, J., 1995, "Requirements Engineering: An Educational Dilemma," Autom. Software Eng., **2**(4), pp. 343–351.

[19] Mohedas, I., Daly, S. R., and Sienko, K. H., 2015, "Characterizing Novice Use of Design Ethnography Utilizing Skill Acquisition and Learning Theories," Mudd Design Workshop, Los Angeles.

[20] Mohedas, I., Cravens, G. L., Daly, S. R., and Sienko, K. H., 2015, "Student Perceptions of Stakeholders During Capstone Design," ASEE Annual Conference & Exposition.

[21] Mohedas, I., Daly, S. R., and Sienko, K. H., 2014, "Design Ethnography in Capstone Design: Investigating Student Use and Perceptions," Int. J. Eng. Educ., **30**(4), pp. 888–900.

[22] Atman, C. J., Chimka, J. R., Bursic, K. M., and Nachtmann, H. L., 1999, "A Comparison of Freshman and Senior Engineering Design Processes," Des. Stud., **20**(2), pp. 131–152.

[23] Atman, C. J., Cardella, M. E., Turns, J., and Adams, R., 2005, "Comparing Freshman and Senior Engineering Design Processes: An In-Depth Follow-Up Study," Des. Stud., **26**(4), pp. 325–357.

[24] Atman, C. J., Adams, R. S., Cardella, M. E., Turns, J., Mosborg, S., and Saleem, J., 2007, "Engineering Design Processes: A Comparison of Students and Expert Practitioners," J. Eng. Educ., **96**(4), pp. 359–379.

[25] Bursic, K. M., and Atman, C. J., 1997, "Information Gathering: A Critical Step for Quality in the Design Process," Qual. Manage. J., **4**(4), pp. 60–75.

[26] Sobek, D. K., II, and Jain, V. K., 2007, "Relating Design Process to Quality: A Virtual Design of Experiments Approach," ASME J. Mech. Des., **129**(5), pp. 483–490.

[27] Mohedas, I., Daly, S. R., and Sienko, K. H., 2014, "Gathering and Synthesizing Information During the Development of User Requirements and Engineering

Specifications," 121st ASEE Annual Conference & Exposition, Indianapolis, IN, June 15–18, Paper No. 10353.
[28] Mohedas, I., Daly, S. R., and Sienko, K. H., 2014, "Student Use of Design Ethnography Techniques During Front-End Phases of Design," 121st ASEE Annual Conference & Exposition, Indianapolis, IN, June 15–18, Paper No. 10357.
[29] Ingwersen, P., and Jarvelin, K., 2005, *The Turn: Integration of Information Seeking and Retrieval in Context*, Springer, Amsterdam, The Netherlands.
[30] Wilson, T. D., 1999, "Models in Information Behavior Research," J. Doc., **55**(3), pp. 249–270.
[31] Tanni, M., and Sormunen, E., 2008, "A Critical Review of Research on Information Behavior in Assigned Learning Tasks," J. Doc., **64**(6), pp. 893–914.
[32] Alexandersson, M., and Limberg, L., 2003, "Constructing Meaning Through Information Artefacts," New Rev. Inf. Behav. Res., **4**(1), pp. 17–30.
[33] Hultgren, F., and Limberg, L., 2003, "A Study of Research on Children's Information Behaviour in a School Context," New Rev. Inf. Behav. Res., **4**(1), pp. 1–15.
[34] Limberg, L., 1999, "Experiencing Information Seeking and Learning: A Study of the Interaction Between Two Phenomena," Inf. Res., **5**(1), pp. 5–1.
[35] McGregor, J. H., and Streitenberger, D. C., 1998, "Do Scribes Learn?: Copying and Information Use," Sch. Libr. Media Res., **1**, pp. 1–16.
[36] Wertz, R. E. H., Purzer, Ş., Fosmire, M. J., and Cardella, M. E., 2013, "Assessing Information Literacy Skills Demonstrated in an Engineering Design Task," J. Eng. Educ., **102**(4), pp. 577–602.
[37] Blandin, J. S., Brown, W. B., and Kock, J. L., 1974, "Uncertainty and Information-Gathering Behavior: An Empirical Investigation," Academy of Management National Meetings, Seattle, WA, pp. 54–55.
[38] Austin-Breneman, J., Honda, T., and Yang, M. C., 2012, "A Study of Student Design Team Behaviors in Complex System Design," ASME J. Mech. Des., **134**(12), p. 124504.
[39] Walthall, C. J., Devanathan, S., Kisselburgh, L. G., Ramani, K., Hirleman, E. D., and Yang, M. C., 2011, "Evaluating Wikis as a Communicative Medium for Collaboration Within Colocated and Distributed Engineering Design Teams," ASME J. Mech. Des., **133**(7), p. 071001.
[40] Lemons, G., Carberry, A., Swan, C., Jarvin, L., and Rogers, C., 2010, "The Benefits of Model Building in Teaching Engineering Design," Des. Stud., **31**(3), pp. 288–309.
[41] Ensici, A., and Badke-Schaub, P., 2011, "Information Behavior in Multidisciplinary Design Teams," 18th International Conference on Engineering Design (ICED11), Impacting Society Through Engineering Design, Vol. 7: Human Behaviour in Design, Lyngby/Copenhagen, Denmark, Aug. 15–18, pp. 414–423, p. DS 68-7.
[42] Daly, S., Adams, R., and Bodner, G., 2012, "What Does It Mean to Design? A Qualitative Investigation of Design Professionals' Experiences," J. Eng. Educ., **101**(2), pp. 187–219.
[43] Dally, J. W., and Zhang, G. M., 1993, "A Freshman Engineering Design Course," J. Eng. Educ., **82**(2), pp. 83–91.
[44] Daly, S. R., McGowan, A., and Papalambros, P., 2013, "Using Qualitative Research Methods in Engineering Design Research," 19th International Conference on Engineering Design (ICED13), Design for Harmonies, Vol. 2: Design Theory and Research Methodology, Seoul, Korea, Aug. 19–22, pp. 203–212, p. DS 75-2.
[45] Sommerville, I., and Kotonya, G., 1998, *Requirements Engineering: Processes and Techniques*, John Wiley & Sons, New York.
[46] Garvin, D. A., 1987, "Competing on the 8 Dimensions of Quality," Harv. Bus. Rev., **65**(6), pp. 101–109.
[47] Gause, D. C., and Weinberg, G. M., 1989, *Exploring Requirements: Quality Before Design*, Dorset House, New York.
[48] Génova, G., Fuentes, J. M., Llorens, J., Hurtado, O., and Moreno, V., 2013, "A Framework to Measure and Improve the Quality of Textual Requirements," Requir. Eng., **18**(1), pp. 25–41.
[49] Hollander, M., Wolfe, D. A., and Chicken, E., 2013, *Nonparametric Statistical Methods*, 3rd ed., John Wiley & Sons, Hoboken, NJ.
[50] Ryan, G. W., and Bernard, H. R., 2003, "Techniques to Identify Themes," Field Methods, **15**(1), pp. 85–109.
[51] Creswell, J. W., 2013, *Research Design: Qualitative, Quantitative, and Mixed Methods Approaches*, 4th ed., Sage Publications, Thousand Oaks, CA.
[52] Westbrook, L., 1994, "Qualitative Research Methods: A Review of Major Stages, Data Analysis Techniques, and Quality Controls," Libr. Inf. Sci. Res., **16**(3), pp. 241–254.
[53] Patton, M. Q., 1990, *Qualitative Evaluation and Research Methods*, 2nd ed., Sage Publications, Newbury Park, CA.
[54] Atman, C. J., Deibel, K., and Borgford-Parnell, J., 2009, "The Process of Engineering Design: A Comparison of Three Representations," 17th International Conference on Engineering Design (ICED 09), Vol. 1: Design Processes, Stanford, CA, Aug. 24–27, pp. 483–494, p. DS 58-1.
[55] Bailey, R., 2008, "Comparative Study of Undergraduate and Practicing Engineer Knowledge of the Roles of Problem Definition and Idea Generation in Design," Int. J. Eng. Educ., **24**(2), pp. 226–233.
[56] Schuler, D., and Namioka, A., 1993, *Participatory Design: Principles and Practices*, Lawrence Erlbaum Associates, Hillsdale, NJ.
[57] Goffin, K., Varnes, C. J., van der Hoven, C., and Koners, U., 2012, "Beyond the Voice of the Customer: Ethnographic Market Research," Res. Technol. Manage., **55**(4), pp. 45–54.
[58] Blomberg, J., Giacomi, J., Mosher, A., and Swenton-Wall, P., 1993, "Ethnographic Field Methods and Their Relation to Design," *Participatory Design: Principles and Practices*, D. Shuler and A. Namioka, eds., Lawrence Erlbaum, Hillsdale, NJ, pp. 123–155.
[59] Malterud, K., 2001, "Qualitative Research: Standards, Challenges, and Guidelines," Lancet, **358**(9280), pp. 483–488.
[60] Zhang, T., and Dong, H., 2009, "Human-Centred Design: An Emergent Conceptual Model," Include2009, Royal College of Art, London, Apr. 8–10, pp. 1–7.