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EXPERT AND STUDENT CONCEPTIONS OF THE DESIGN PROCESS: DEVELOPMENTAL DIFFERENCES WITH IMPLICATIONS FOR EDUCATORS

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Abstract. If educators want students to learn to think like experts, then we need to learn how experts think. In this set of studies, we posed two questions: (1) what is “the wisdom” of engineering design (i.e., what are the key concepts), and (2) how do people at different points of professional development define the engineering design process? Both questions were intended to enhance understanding of and support for students’ professional development and conceptual understanding of design. The method of assessment used was concept mapping. A concept map is a spatial representation of ideas and their relationships. Fifteen experts in academe and industry each constructed a map reflecting their understanding of the design process. From those maps, we extracted critical concepts to establish a taxonomy consisting of six broad categories: the design process, motivation for the design, interpersonal skills, technical skills, safety (e.g., regulation, ethics), and marketing. These categories were then used as benchmarks for assessing the development of undergraduates taking a year-long senior design course. Students constructed individual maps at three time points. Analyses revealed that students and experts expressed similar understandings of the importance of interpersonal and technical skills; however, students made consistently fewer references to safety and marketing than did experts. Over time, the expert-student gap closed in two areas: knowledge of the design process and its underlying motivations. In addition to their implications for educators, these findings offer an important avenue for understanding the nature of expertise. That is, they suggest that experts have a more developed understanding of the social context in which a design and designers function. The study’s implications for research in concept mapping are also discussed.

1 Introduction

Across a variety of fields research has suggested that the development of expertise involves the acquisition of concepts and an understanding of their abstract relational dimensions [1]. Another hallmark of expertise is the ability to recognize meaningful “chunks” of information [2]. These findings suggest that experts not only know more than novices, they organize and use their knowledge differently from novices. They also support theoretical arguments that people structure their knowledge in propositional representations (i.e., sets of information) [3] and that networked propositions are the bases for human reasoning [4].

Another key feature of expertise is that it is domain-specific. Expertise in one area does not necessarily translate into expertise in another [5, 6]. In this study, we wanted to identify “the wisdom” of expertise in engineering design (i.e., key concepts), and explore whether people’s conceptions of the design process differ according to their level of experience and professional development. We had two overarching goals. One goal was to establish a method of assessment that would inform our understanding of expertise in design. A second goal was to use what we learned about how experts think to inform engineering education at the undergraduate level. In other words, if we know the wisdom of design expertise, can we translate that into more meaningful educational experiences?

A significant challenge to researchers interested in the novice-expert shift is establishing valid and reliable ways of capturing and representing what people know, how they apply their skills, and how their performance varies over time and with experience [7, 8, 9, 10]. A variety of methods have been used to explore developmental differences including, asking people to “think aloud” as they engage in problem-solving activities, to critique the solutions of others, and observing problem-solving performance *in situ*.

This work has identified patterns in students’ thinking, some of which may interfere with their ability to enter the professional design community. For instance, when asked to define the design process, students often emphasize the role of creativity more than iterative processes such as evaluation and revision; they also appear to design for themselves rather than considering the needs of the user [11]. When solving design problems, less-experienced students often “getting stuck” modeling a single alternative solution rather than considering many alternatives whereas more advanced students advance to later stages of the design process (e.g., decision-making and project realization) [12].

To capture and assess expert and students’ conceptual understanding, *and* support student learning we used concept mapping. Elsewhere, we have described how concept maps can be used to assess expert-student differences in the field of biomedical engineering, and to assess the development of students’ thinking about the design process [13]. Here, we extend that work by using concept maps to elicit a broader sample of experts’ understandings of design and, in turn, create meaningful benchmarks for evaluating students' developing conceptions over time. Our work was intended, in part, to address recent observations that much of the research in expertise focuses on classifying people as novices *or* experts rather than tracking how people develop expertise over time [14]. We were also interested in developing a reliable method for assessing the contents of individuals' maps. Finally, recognizing that helping students become aware of their tacit knowledge frameworks is an important means to enhanced learning [15, 16], we archived students' representations over time, and then asked them to comment on the similarities and differences between their initial and final maps. We also encouraged students to use one of their maps as a study guide for an exam near the end of the first semester.

We posed three questions: (1) What are key concepts in the engineering design process? (2) Are there developmentally related differences in people's conceptions of this process? (3) If so, then what do these differences mean for theoretical understanding of design expertise and for design education? We expected that, relative to students, expert maps would have more accurate propositions, and have more densely networked concept across a wider breadth of categories. Over time, we expected student maps to increase in accuracy and complexity.

2 Methods

Our first goal was to determine how experts define the design process, and establish benchmarks of expertise. This work is described as Study 1. Our second goal was to examine students' definitions relative to those expert benchmarks. Work with students is described as Study 2. We conclude with a comparison of the two groups.

2.1 Study 1: Experts

We began by soliciting participants from academe and industry; the second and fourth authors invited approximately 60 design colleagues to participate via electronic mail. From this pool, 15 experts consented to participate. Ten participants had doctoral degrees, 3 had graduate degrees and 2 had completed undergraduate programs in various engineering disciplines. Participants had an average of 9 years experience in academia, 11 years in industry and 10 years in teaching or supervising design. Nine of the participants had industrial and academic experience. 14 of the participants were male.

Because our experts were located across the globe, orientation procedures and data collection was conducted electronically. Participants were sent an electronic letter that explained the study, described the concept mapping procedure, and provided a web link to a tutorial on how to build a concept map. Experts were asked to respond to the focus question, "What is your current conceptual understanding of what is involved in the biomedical engineering design process?" Once constructed, maps were sent electronically to the first author. Participants also provided basic demographic information, and a brief description of how their map reflected their professional history and understanding of the design process.

2.1.1 Analyses and Results for Experts

All maps were analyzed by the second and fourth authors. Blind to the identity of the map authors, these raters counted the number of concepts and lines in each map. A line:concept ratio was calculated by dividing the number of lines by the number of concepts. Inter-rater reliability on these metrics was acceptable (node, $r = .99$; line, $r = .99$; density, $r = .96$; range = 0 to 1).To evaluate the accuracy of map propositions, we used a modified version of a relational scoring method [17] in which the validity of each map's proposition is evaluated based on the correctness of the linking word. We awarded no points for an invalid or misconceived link; 1/2 point for a partially valid, general or imprecise link; and 1 point for a valid, precise, and clearly stated link. Our two raters had acceptable agreement on the validity ratio of map propositions ($r = .80$, range = 0 to 1).

Expert maps contained an average of 26 concepts ($M = 26.23$, $SD = 15.37$), 33 lines ($M = 32.97$, $SD = 17.78$), and 1 line per concept ($M = 1.31$, $SD = .25$). Variability in these structural elements was considerable (concept, range = 13-60; line, range = 15-75, density, range = 1.04-1.86), prompting us to identify a subset of maps for more intensive analyses. Eight maps were selected on the basis of their general coherence and relatively higher validity scores ($M = .93$, $SD = .03$; range = .88-.97). These maps contained an average of 29 concepts ($M = 29.19$, $SD = 14.06$, range = 16-52), 37 lines ($M = 37.06$, $SD = 14.49$, range = 24-61) and 1 line per node (line:node, $M = 1.35$, $SD = .27$, range = 1.04-1.86).

To identify key concepts in the design process, we wrote each concept contained in each expert's map on a separate index card. This yielded a set of 78 concepts; identically worded concepts were not counted. The first and second authors then sorted these cards based on their conceptual similarity. From this process, 6 categories emerged: the design process (e.g., product definition, prototyping), interpersonal skills, technical background, motivation for the design, marketing and overriding societal concerns (i.e., ethics, regulation). Each concept card was then reviewed with an eye toward eliminating conceptually similar ideas within categories. For example, 'personal skills' and 'communication skills' were collapsed into the single term 'communication skills.' This process yielded a reduced list of 42 concepts. Iteration continued until the full list of concepts was reduced to a set of 27 unique biodesign concepts.

Maps were then examined for references to these 27 concepts. Semantic similarity, not exact terminology was required. For instance, if both technical skills (e.g., "computer programming skills") and technical knowledge (e.g., "biology") were mentioned, then the map received a 100% coverage rating for the category of technical background. If only one of these concepts was represented then a 50% coverage rating was given. Table 1 summarizes descriptive statistics across the six categories. Inter-rater reliability across the 6 categories was acceptable (possible range = 0 – 1; actual range = .78 -.95).

Table 1. Means, standard deviations and ranges for percentage of concept coverage among 8 expert mappings (possible range = 0-1).

	Design process	Interpersonal skills	Technical background	Motivation for design	Marketing	Ethics
M	.40	.29	.44	.42	.35	.46
SD	.19	.33	.40	.22	.30	.29
Actual range	.10-.66	0-.84	0-1	0-.67	0-.67	0-.84

Finally, we examined what experts said their maps represented. One expert noted that his map was "greatly influenced by industry experience in product development," and that it was "based on practical, relevant, important issues and concepts crucial for successful medical device design and successful career paths. It is not based on theory and includes not only technical but related economic and regulatory concepts." Another offered, that "industry considers how the design process interfaces with other organizational components and the skills to successfully manage the design process." Thus, his map was "broader" compared to a "focus on the technical knowledge and skills required to design the device itself." These qualitative comments suggest that experts not only recognize the technical and procedural demands of the design process, they also situate that process in a social context with ethical and financial constraints and opportunities. This is an especially critical finding for engineering educators because it supports arguments that experts not only have extensive domain knowledge, they also understand when and how to use what they know [18].

2.2 Study 2: Students

As part of their course requirements, 51 students enrolled in a capstone design course at Vanderbilt University were asked to construct concept maps focused on the same question given to experts. Complete data was obtained for 32 students (participation rate = 63%). At the opening of the course, students were given a brief orientation to concept mapping and directed to the same web-based tutorial provided to experts. They were then directed to construct a concept map responding the question, "What is your current conceptual understanding of what is involved in the biomedical engineering design process?" The map was to be constructed as a homework assignment. Shortly before the final exam at the end of the fall semester, students constructed a second map focused on this same question. Students were allowed, and encouraged, to use this map as a study guide and final exam "cheat sheet." Students completed a third map at the end of the spring semester, a time coinciding with their presentation of their design project and the composition of a final paper. At this time, we asked students to reflect on and summarize, in writing, how their final map compared to their initial map.

2.2.1 Analyses and Results for Students

Analyses are identical to those described for expert mappings. Inter-rater reliability on these metrics was acceptable (intraclass correlation = .89, range = 0-1). Inter-rater correspondence for the validity of map propositions was also acceptable (intraclass correlation = .77). One-way repeated measures analyses of variance (ANOVA) showed significant linear and quadratic trends for the number of concepts and lines (concepts: linear, $F[1, 31] = 8.20$, $p < .01$; quadratic, $F[1, 31] = 74.58$; lines: linear, $F[1, 31] = 8.05$, $p < .01$; quadratic, $F[1, 31] = 67.19$, $p < .01$). No significant trends were found for density and validity. The average line:concept ratio or network density was consistently low (i.e., almost 1:1); the average validity of map propositions was high (possible range = 0 to 1). Table 2 summarizes descriptive statistics for these dimensions of student maps over time.

Table 2. Means, standard deviations and ranges for the number of concepts and lines, density of network, and proposition validity of student mappings.

	Time 1		Time 2		Time 3	
	M	SD	M	SD	M	SD
Concept	16.47	4.62	34.19	12.34	20.92	9.40
range	*11-34*		*13-54*		*8-54*	
Line	19.58	6.16	39.38	13.99	24.91	11.44
range	*13-39*		*17.5-70*		*8-57*	
Density	1.20	.22	1.18	.20	1.21	.23
range	*.93-2.11*		*.94-1.63*		*.92-1.97*	
Validity ratio	.93	.14	.88	.19	.88	.22
range	*.49-1.00*		*.24-1.00*		*.25-1.00*	

Significant increases in the number of concepts and lines suggested that students gained conceptual knowledge about the design process during the first semester. However, stability in the validity of map propositions suggested that students did not necessarily develop a deeper understanding of associations among concepts. While we expected a steady increase in these map elements, we found significant quadratic trends. We suspect the increases observed at Time 2 stem from the fact that students constructed their maps as a study aid for the final exam.

Our two raters also examined student maps for the presence and absence of the 27 key concepts. The percentage of semantically similar concepts represented in the student map or "coverage" of the domain taxonomy was calculated. One-way repeated measures ANOVAs showed linear trends for the categories of the design process, interpersonal skills, genesis of the design, and ethics. A quadratic trend was also found for the design process and for ethics.

Table 3. Results of one-way repeated measures ANOVA testing trends for time in categorical content of student mappings.

	F linear	F quadratic
Design process	7.05*	16.13***
Interpersonal skills	5.74*	ns
Technical background	ns	ns
Genesis of the design	4.77*	ns
Marketing	ns	ns
Ethics	16.1***	33.39***

* = $p < .05$; ** = $p < .01$; *** = $p < .001$

3 Comparing experts and students

T-tests assuming unequal variance showed that at Time 1 expert maps had significantly more concepts and lines than did students (concept, $t[7]= 2.52$, $p < .05$; lines, $t[8]=3.34$, $p < .05$); however, experts and students did not differ in density or validity. There were no statistically significant expert-student differences on any of these dimensions at Time 2. Results for Time 3 showed that experts had significantly more lines and concepts (lines, $t[38]=2.60$, $p < .05$; concepts, $t[38]= 2.01$, $p < .05$), but did not differ from students in density or validity.

Table 4 summarizes the percentage of content coverage across the 6 categories for experts and for students, and summarizes t-tests and p values regarding student-expert comparisons. At the beginning of the design course, students and experts placed equal emphasis on two areas: interpersonal skills and technical background. Students differed from experts in four areas: the design process, motivation for the design, marketing and ethics. At the end of the first semester (Time 2), students closed the expert-novice gap in five of the six areas. The only difference pertained to marketing. At the end of their design experience (Time 3), students continued to differ from experts in two areas: marketing and ethics.

Table 4. Average percentage and t-tests comparing percentage of content coverage in expert and student and maps across the 6 identified categories.

	Design process	Interpersonal Skills	Technical Background	Motivation for design	Marketing	Ethics
Expert	.40	.29	.44	.42	.35	.46
Student						
Time 1						
M	.24	.16	.27	.16	.13	.10
T	2.30*	--	--	3.17*	2.21*	3.32**
Time 2						
M	.33	.36	.41	.38	.15	.60
T	--	--	--	--	2.09*	--
Time 3						
M	.30	.28	.40	.34	.11	.22
T	--	--	--	--	2.20^{+}	2.60*

-- = not significant, * = p < .05; ** = p < .01; $^{+}$ = approached significance (p < .06)

Because we were committed to using a research tool that also offered students a window into their own thinking, at the end of the course we asked students to identify and reflect on differences in their initial and final maps. Some student comments reflected initial skepticism about the value of the concept mapping task (e.g., "*I really didn't think that I would see big changes. But I can now understand").* Another student articulated the difference between his first and final maps in this way: *"The final concept map illustrates a more interactive, dynamic and complex relationship between the various concepts."* For this student, communication was the critical component in the design process (e.g., *"Although the ultimate goal is related to product or system, without effective communications the product or system could not be achieved"*).

In sum, quantitative analyses showed that students increased their knowledge of the design process; however, they did not appear to have greater knowledge integration (i.e., density did not change) or accuracy (i.e., validity did not change). Content analyses revealed similarities and differences between experts and students. These trends offer insight into the development of expertise in design. In the next section, we discuss the study's implications for psychological understanding of expertise and for educators' efforts to enhance students' conceptual and professional development.

4 Summary

This study used concept maps to identify key concepts in the biomedical engineering design process and explore expert-student differences. Despite considerable within-group variability, experts consistently demonstrated a more comprehensive and differentiated understanding of the design process than did students. For instance, in addition to focusing on the design process itself, experts attended to issues in the surrounding social context, including understanding the need for the design, overriding societal concerns such as ethics and regulatory requirements, interpersonal skills (e.g., teamwork, project management), and marketing. These findings offer an important avenue for understanding the nature of expertise. That is, they suggest that experts think of design not only in abstract theoretical terms, they also understand and consider the social context in which a design and designers function.

Essentially, our study shows that students moved from 'this to that.' We view students' initial maps as their assumptions about the design process. Their second maps reflect an abstracted knowledge grounded in course readings and lectures. Their final maps are the most expert-like. We believe these representations differ from initial maps because they reflect the voice of experience and an internalized knowledge of what it means to design something. What we want to know more about is the processes underlying these changes. Our current hypothesis is that the expert-novice gap is closed when students increase their domain knowledge *and* bring that knowledge to bear on an authentic problem in a realistic setting.

The development of our taxonomy yielded an ability to assess map contents. This is a significant development. We are testing the validity of our taxonomy by comparing results derived from analyses with its specific design concepts to rubrics used by other design educators. We expect this work to yield a 'thesaurus' of design terms. Establishing such a thesaurus should address issues of inter-rater reliability and the fact that our current judgments about what is an acceptable concept are fairly subjective. Another related concern is that our current assessment of proposition validity does not appear to discriminate novice and student conceptions. Thus we are seeking a way to express the more holistic nature of people's thinking about design (i.e., does it appear to be a linear or iterative process?), and are characterizing maps in terms of the extent to which they describe the design process (i.e., is it to the design level, prototype level?).

We are currently comparing the concept maps of students enrolled in this year's design class to measures of engagement and competence in design. For instance, students have responded to design scenarios across the year, allowing us to assess their developing abilities over time. We are also asking students to create a concept map of their senior design project and then relate that representation to other technologies that visually represent design problems. Finally, we are comparing what students say about the design process with what they actually do when designing something. Across the year we observed how three student design teams formed, and how they selected and attempted to solve a real medical problem. This work allows us to see how and whether students apply their conceptual knowledge and skills as they participate in organized, cumulative activities that may hold greater meaning for them.

In sum, our findings suggest that experts' knowledge cannot be reduced to a set of isolated facts because their knowledge is linked to contexts and conditions for its use. If this is the case, then design educators should place considerable emphasis on the conditions for applying the facts and procedures associated with the design process. In turn, assessment of student competence should focus not only on students' ability to recall facts, but on whether students know when, where, and how to use their knowledge.

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