Understanding Lifelong Learning and Skills Development: Lessons Learned from Practicing Civil Engineers

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Abstract: Civil engineering is rapidly evolving as research discoveries, technological evolution, and changing regulations alter the state of practice. To adapt to the advancement of the field, engineers must have the ability to be lifelong learners. While a number of studies have focused on developing lifelong learning skills among undergraduates, far fewer empirical studies have examined such learning in engineering workplaces. Further, additional context-specific research on the skills and knowledge required for success in civil engineering is needed. This study begins to address these gaps through an exploratory study of current practitioners using 19 semistructured interviews with a purposeful sample of civil engineers in the Pacific Northwest. Subsequent thematic analysis of the interview transcripts revealed four themes of skill and knowledge groups, namely technical, communication, professional, and business skills and knowledge, plus the methods of learning used to develop those skills. The findings from this study were placed into context within the existing literature. As has been mirrored in studies across several engineering disciplines, this study revealed that communication skills remain critical for professional practice, especially nonformal modes of communication such as email. Discipline and region-specific technical skills, such as seismic design and the use of specialized analysis software, were revealed to be important for both entry-level engineers and engineers in management and senior roles. Other important findings of this study also showcased the need for self-directed learning, learning through mentorship and asking questions, and learning through experience. Finally, several implications of the research findings on civil engineering education were discussed, such as greater emphasis on metacognitive activities that encourage students to reflect on how they learn. DOI: 10.1061/(ASCE)EI.2643-9115.0000068. *© 2022 American Society of Civil Engineers.*

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Introduction

Civil engineering evolves quickly as research discoveries, updated technology, and evolving regulations change the state of practice (National Academy of Engineering 2018). To adapt to the advancement of the field, engineers must have the ability to be lifelong learners, as reflected in the ABET student learning outcomes (ABET 2018), as well as reports from the American Society of Civil Engineers (ASCE 2008) and the National Academy of Engineering (National Academy of Engineering 2018). While a number of studies have focused on developing lifelong learning (LLL) skills among undergraduates, far fewer empirical studies have examined such learning in engineering workplaces. In fact, in their mapping review of research on engineering practice over the last decade, Mazzurco et al. (2021) identified "how engineers learn in the workplace" (p. 9) as a major theme but found only 18 peer-reviewed studies (less than 10% of the articles they identified) that addressed this issue. Moreover, they found critical gaps in the "learning or development of specific competencies and on what conditions enable or hinder learning in the workplace" (p. 9). In addition, while more than twice as many studies (45, or 24%) identified the competencies and attributes needed for engineering practice, they found that most studies were highly generalized across multiple engineering fields and contexts. As a result, they also cited the need for more context-specific research (e.g., by discipline and/or sector) on the competencies required for success in each field.

Background

As Oliver (1999) and Aspin and Chapman (2000) noted two decades ago, lifelong learning is a complex concept with varying definitions. To frame our work, we adopt Cruz et al.'s definition as "the intentional and active personal and professional learning that should take place in all stages of life, and in various contexts with the aim of improving knowledge, skills, and attitudes" (Cruz et al. 2020, p. 737). Several studies have focused on preparing engineering students for LLL, but fewer have examined LLL in the workplace, including both what engineers need to learn as they move through their careers and how they learn it. With respect to *what*, Mazzurco et al. (2021) found that across studies, communication, teamwork, and related professional skills consistently emerge as most important. However, these studies are typically generalized across contexts. For example, Brunhaver et al.'s (2018) cross-sectional study of early-career engineers included participants from multiple disciplines working in sectors ranging from food manufacturing to transportation. While their study found that 61% of their

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participants reported learning basic content knowledge in school (versus 16% at work), 60% reported learning equipment- and process-specific knowledge at work (versus 5% in school). They also found that 50% or more reported learning professional skills such as communication, working with people, and finding information at work; similarly, 56% reported learning organization-specific knowledge and skills on the job (e.g., policies, procedures, hierarchies, and culture).

Discipline-specific studies, though more limited, yield similar findings. Using organizational socialization as a lens, for example, Korte and LeBlanc (2020) identified four stages of technical, professional, and organizational learning that newly hired electrical engineers moved through as they developed workplace competence. Similarly, Lutz's study of newly hired mechanical engineers identified two domains of technical learning (task performance and role clarity) and five domains of organizational learning (e.g., history, goals, and values) (Lutz 2017; Lutz and Paretti 2021).

Still, less work has examined *how* engineers learn at work. In earlier work, Cervero et al. (1986) conducted telephone interviews of nearly 500 practicing engineers (predominantly mechanical and electrical) to determine how engineers used the three modes of learning: instruction, inquiry, and performance. They found that most practitioners preferred informal, or self-directed, modes of learning over formal courses. More recently, work by Korte (2019), Korte and LeBlanc (2020), Korte (2009), Lutz (2017), Lutz and Paretti (2021), and Lutz and Paretti (2017) on newly hired engineers emphasizes the importance of informal interactions with experienced peers in workplace learning. Similarly, a study of recent mechanical and engineering science graduates highlighted the substantial self-directed learning involved in the transition to work and how new hires relied on talking with colleagues and finding print or online resources, but few instances of formal training has been reported (Ford et al. 2019; Paretti et al. 2020). In related work from information and library sciences, a 2019 study by Phillips et al. (2019) found that practicing engineers relied heavily on Google, peers, and libraries "to acquire the information, skills, and abilities to complete their projects" but also regularly used corporate intranets, standards, and to a lesser extent e-journals and databases.

While existing research offers some insights on the lifelong learning needs and practices of engineers, findings are often generalized across engineering disciplines and work contexts and, as the studies noted above suggest, often focus on new graduates. Considering that as engineers obtain more experience in the workplace, they also have different perceptions of what skills are important and their approach to learning those skills might vary; thus, it is important to understand the workplace from different perspectives. Furthermore, currently, little if any research exists to help understand whether and how specific disciplines perceive the required skills and learning in the workplace. Consequently, as Mazzurco et al. (2021) argue, more work is needed to understand what skills and knowledge are needed for specific engineering fields and how practitioners develop these skills and knowledge. This study represents one step toward increasing that understanding by exploring lifelong learning in one discipline—civil engineering—in a single geographic region. In doing so, we seek to contribute to and further catalyze an emergent body of research that looks both at other individual disciplines and across disciplines at given career levels or positions.

At the same time, the study contributes directly to our understanding of civil engineering education, where an understanding of lifelong learning, especially relative to technical skills, may have particular salience. Mazzurco et al. (2021) only found five studies investigating specific technical competencies needed for engineering practice, and four of those five focused on mathematical skills. Thus, we have little empirical research that defines the technical knowledge needed in engineering practice. Within civil engineering, variations in design practices based on geographical hazards, state and local building codes, and project type may impact what technical (and professional) skills practicing engineers learn across their careers and how they learn them. Other engineering fields may also be shaped by physical location, but some also likely have other factors that impact lifelong learning needs (e.g., evolving FDA regulations for biomedical engineers or evolving cybersecurity policies for computing engineering and computer scientists). Lifelong learning in civil engineering may also be shaped by professional certification given that more civil engineering graduates take the PE exam than graduates of any other discipline. In 2020, for example, NCEES data show more than 5,800 civil engineers took the PE for the first time; in contrast, the next highest discipline was mechanical engineering, with just over 3,000 first-time takers (NCEES 2021), despite the fact that more than twice as many B.S. degrees are awarded annually in mechanical engineering (~32,000 in 2018) compared to civil engineering (~15,000 in civil and/or environmental in 2018) (Roy 2018). While educators cannot prepare graduates for every possible type of problem they may face in professional practice, they can prepare them for the kinds of learning they will face and provide the foundation for skills they will continue to develop as practitioners across their careers. That preparation depends on a robust understanding of just what that learning looks like and what specific skills are necessary in their chosen field—in this case, civil engineering practice.

Research Objective

Given the importance of lifelong learning for engineering practice broadly and in civil engineering in particular, we conducted an exploratory study of current practitioners' perceptions of lifelong learning. Specifically, using semistructured interviews with a purposeful sample of civil engineers in the Pacific Northwest, we addressed the following research questions:

1. What skills and knowledge are required, learned, or improved during a civil engineering career?
2. How do practicing civil engineers engage in learning, or further improving, skills and knowledge?
3. How do these skills, knowledge, and learning practices vary across career phases?

Answering these questions is critical in helping civil engineering educators better understand how to prepare their students for the continuous professional development needed in their careers.

Methodology

To address this critical knowledge gap, we conducted an exploratory qualitative study. Our goal was to understand how practicing civil engineers described their LLL (Smith et al. 2009); that is, we were interested in what participants said they learned and how they reported learning it. As such, this work is exploratory in that it primarily probes the question of what participants learned and what learning modes they employed; future work could explore each domain in more depth. Interview data were analyzed using thematic analysis, a qualitative research methodology for systematically "identifying, organizing, and offering insight into patterns of meaning across data" (Clarke et al. 2015; p. 57). Data were coded using both inductive and deductive approaches, and codes were then categorized into common themes to address the research questions. Using the definitions from Brunhaver et al. (2018), knowledge was defined as "relating to the understanding and awareness of concepts and information related to a specific domain," and skills were defined as "the ability to apply domain knowledge in a particular context." Although the data are qualitative and comprise the major themes that emerged echo findings from other studies, the diversity and complexity of the subcodes under each theme seemed to represent a major finding in themselves in ways that meaningfully extend prior work. As a result, to preserve that diversity within the scope of a single manuscript and provide a visual mapping of the findings, we opted to quantify the data using frequency counts (numbers of participants), represented in bar graphs, to describe the sample and identify patterns (Sandelowski et al. 2009).

Participants

Using purposive sampling (Onwuegbuzie and Leech 2007), 19 practicing civil engineers currently working in the Pacific Northwest were recruited for this study, stratified based on years of experience and organizational context. We maintained a single geographic context because in civil engineering, geologic regions influence the codes used, common controlling loads, and standard practices of design and construction and thus can impact the needed knowledge and skills. For instance, the Pacific Northwest has higher seismic risk and lower design wind speeds than the eastern coast of the United States and thus requires a different subset of technical expertise. We varied years of experience because most existing studies focus on new graduates, whose learning trajectories may be considerably steeper than more experienced engineers but may not account for learning needed in the later phases of a career.

Participants were contacted via email through Author 3′s extended network. Five participants had less than five years of experience, seven participants had 5—20 years of experience, and seven participants had over 20 years of experience. With the range of years of experience, the participant′s job titles and responsibilities varied widely as well, with five entry-level engineers, three senior engineers, six project managers, on technical expert at a career stage equivalent to a project manager, and four vice presidents. All participants had at least a B.S. in civil engineering, with 11 having M.S. degrees and one having a Ph.D. in the field. The participants were from five different engineering firms that ranged in size from approximately 200 to 10,000 plus employees. The company consulting profiles ranged from purely structural engineering for the smaller companies to more general civil engineering and construction for the larger multioffice, multinational corporations. None of the firms specialized in the civil engineering areas of geotechnical engineering or water resources.

A screening survey distributed prior to the interviews requested the following demographic information: name, gender, ethnicity, degree(s) obtained and year of graduation, universities attended, years of professional experience, company name, years working at current company, current position, years working in current position, and professional licenses held. Seven of the participants identified as female and the remaining identified as male. Two of the 19 participants identified as nonwhite. Table 1 shows the years of experience in industry and the career phase of the participants. Note that while company-specific titles for some of these roles varied, we generalized and grouped positions based on the similarity of duties. Entry-level engineers are new engineers without professional licensure. Senior engineers are engineers with a professional license who are not yet managing projects. Project managers are typically the engineers of record for a project and are responsible for all aspects of the project within the firm. The one technical expert was someone at the project management level who did not assume engineer of record responsibility for projects; rather they provided technical advice and analysis on the most complicated aspects of all projects within the firm. Their responses were grouped with the project manager′s responses to protect their identity within the study and provide meaningful conclusions. All vice presidents had the same title and were second in command at their respective firms. For the large companies, the vice presidents were in control of a region of the country for a specific market sector. Interestingly, years of experience varied widely for both project manager and vice president positions. Participants all signed a consent form prior to the interviews that was reviewed and approved by Washington State University′s Internal Review Board (IRB).

Table 1. Participant information

Participant	Years of experience	Career phase
1	1	Entry level
2	1	Entry level
3	1.5	Entry level
4	2.5	Entry level
5	2.5	Entry level
6	7	Senior engineer
7	11.5	Senior engineer
8	12	Senior engineer
9	8	Project manager
10	9.5	Project manager
11	12	Project manager
12	20	Project manager
13	23	Project manager
14	27	Project manager
15	17	Technical expert
16	21	Vice president
17	37	Vice president
18	40	Vice president
19	45	Vice president

Data Collection

The semistructured interview protocol was based on a set of main questions asked in every interview. During the interviews, different follow-up subquestions that were related to the main questions were used to probe participants to reveal more specific details or greater depth of explanation based on their responses to the main questions. The interviewer (Author #1) was an M.S. student who had completed civil engineering internships but never worked full-time in practice. The interviewer personally knew some of the participants through professional relationships and had a strong personal belief that they would need to participate in lifelong learning during their engineering career to stay current and achieve their goals. Several of the participants have professional relationships with Author 3 and knew the interviewer was a graduate student of Author 3′s prior to the interview.

The main questions, shown in Table 2, started with two questions to get the participants thinking about the tasks they perform on a daily basis and how their career has progressed. These questions primed the participant to start thinking about the knowledge they need on a frequent basis and the skills that they use for their current and past job tasks. With the third question, the interviewer (Author #1) then began asking about specific skills or knowledge that were challenging to learn on the job and learning occurred. The semistructured approach facilitated extensive open conversation around this question in particular, and participants talked readily about the skills they use during their projects, where they learned those skills, and what they felt well prepared for versus what they had to learn after graduation. As a result, question 3 and the follow-up discussion constituted the majority of the interview. Prompts to the participant did not separate skills and knowledge based on the study definitions provided, but rather used common terms and were

Table 2. Interview main questions

Question number	Question
1	Describe your typical day at work.
2	Can you tell me about your career when it first began versus where you are now?
3	What's the most challenging thing that you've had to learn on the job in the last several years and how did you overcome that challenge?
4	Continuing education is a requirement for engineers in some states to maintain their Professional Engineering license. If this was or was not a requirement, would it change the number of hours you spend working on your professional development, if any?
5	What is the next step you want to take in your career and how are you planning on achieving that goal?
6	Is there anything I didn't ask you, that you think is important to discuss?

separated into knowledge and skills by the researchers during analysis. Question 4 then sought to identify perceptions of LLL in practice in relation to the mandated professional development hours (PDH) required for licensure. Typical follow-up questions addressed whether participants thought PDH hours should be required, whether they would continue learning in the absence of mandated requirements, and whether they considered PDH courses useful learning opportunities. The final two questions sought to determine whether participants had identified additional skills and/or knowledge they needed for their future and whether they had plans for that needed learning. These questions helped explore whether trends in skills and knowledge needed at different career stages were consistent and well-known across the field, even among practitioners who had not yet reached a given stage.

After the interview protocol was developed, it was pilot tested for clarity and usefulness. Given the challenges of recruiting industry practitioners for academic research, we opted to test the protocol with two researchers and a graduate student rather than use potential study participants. The main interview questions did not change between the pilot survey and the final interviews. The interviews were audio-recorded and ranged from 25 to 70 min based on the individual's willingness and ability to share details regarding each question.

Data Analysis

All audio recordings were transcribed to generate written records of the interviews for archiving and analysis and to familiarize the researchers with the data (Miles and Huberman 1994). Eight recordings were fully transcribed by a member of the research team (Author #1), and 11 of the recordings were sent to a transcription service company for initial transcription. However, those 11 recordings that were transcribed professionally were manually checked for accuracy against the audio files by the researchers. Identifying information was then removed, and the transcripts were uploaded to the web-based qualitative analysis tool Dedoose to facilitate collaboration across team members at different universities.

The transcripts were analyzed using thematic analysis (Braun and Clarke 2012; Miles and Huberman 1994; Miles et al. 2014; Saldana 2013). Given the available prior research, an initial codebook was developed prior to beginning analysis (Saldana 2013) using a list of lifelong learning skills from Peat et al. (2005) and the list of knowledge needed for practice detailed in the *Civil Engineering Body of Knowledge* (ASCE 2018) and were grouped into three broad categories: skills, knowledge, and learning methods. Emergent subcodes and themes were then identified from the data to provide a more fine-grained understanding of both what learning occurred and how it occurred.

Using Dedoose, members of the research team followed an iterative process, starting with the initial codebook and then adding and combining codes as new subcodes emerged and themes began to coalesce (Saldana 2013). There were five rounds of data analysis. The first and second rounds were coded by Author 1. Then, this initial codebook was discussed between two researchers (Authors 1 and 3), and several codes were merged, eliminated, or relabeled. The prestructured analysis method utilized ensured that skills deemed important in past research were considered (Peat et al. 2005). In the third, fourth, and fifth rounds of analysis, we moved from individual codes to thematic analysis to provide meaningful ways to synthesize and organize the individual codes developed through the first two rounds. This thematic grouping enabled us to create meaningful groupings of individual skills and knowledge domains that could then be set in dialogue with previous research. In these three rounds, led by Author 2, the data, codes, and emerging themes were continuously reanalyzed and then presented to the other researchers with qualitative research experience (Authors 4 and 5). For some excerpts, different researchers had different interpretations of the assigned code. These contradictions were discussed in depth until an agreement was reached.

The finalized codebook was divided into five main themes, which were technical skills and knowledge, communication skills, professional skills and knowledge, business skills and knowledge, and methods of learning. Note that while some prior work combines communication skills into the code of professional skills (e.g., ABET 2018), other research has divided communication and professional skills into "process skills" (e.g., communication, multidisciplinary teams, and ethical responsibilities) and "awareness skills" (e.g., understanding global and social contexts, ability to engage in LLL) (Shuman et al. 2005). In our data, discussions about communication skills were common among most participants and were more often separate from skills and knowledge associated with specific career positions. In contrast, discussions about professional skills were much more closely linked to specific career positions as well as to company type or focus. Therefore, communication skills and professional skills emerged as separate themes. This separation, along with the individual codes within each theme, helps illustrate the value of adding the thematic analysis to the initial rounds of coding.

To identify the prevalence of skills and knowledge learned across participants and explore potential trends based on career position, we then quantified the number of participants who mentioned each code and searched for patterns based on participant career phase, as described in detail in the Results. Note that these are frequency counts by participant, not by the number of coded segments; that is, whether a participant mentioned a given skill or learning method once or four times in the interview, the count was still one.

Research Quality and Limitations

Following recommendations from Miles et al. (2014), we relied on multiple practices throughout data collection and analysis to support the trustworthiness of the findings, including iterative development of the codebook, multiple coders, and peer debriefing within the research team to build consensus around the major codes and themes. Specifically, as described, following initial coding by Author 1, peer debriefing occurred between Authors 1 and 3 to refine the codebook and negotiate definitions to consensus. This initial coding was then reviewed by a civil engineering educator who is not a member of the research team to support internal

Table 3. Themes and codes identified from interviews with civil engineering practitioners

Theme	Operational description	Codes
Technical	Skills and knowledge that are necessary to analyze and solve engineering-related problems within a project.	Design, Software skills, Fundamental knowledge, Codes and Specifications, Seismic design, Project review
Communication	Skills that are necessary to either explain information or extract information from different audiences involved with engineering projects.	General communication, Oral communication, Audience adjustment, Email, Other written communication, Visual communication
Professional	Skills, other than communication, that are necessary to work and interact with colleagues to accomplish project tasks.	Teamwork, Leadership, Client relationships, Mentoring, Societal and cultural understanding, Time management
Business	Skills and knowledge that are necessary to contribute to the business and project management operations of the engineering company.	Finance, Company operations, Overall vision,
Learning methods	Strategies or approaches participants used to build skills and knowledge.	Mentorship, Experience, Formal classes and presentations, Self-directed study

consistency in coding and credibility in the context of civil engineering practice. Author 3 then led the next rounds of data analysis focused on the identification of themes, with peer debriefing of theme definitions and excerpts occurring with Authors 2, 4, and 5 through three iterations to negotiate the final themes and definitions to consensus. Again, the results from this process were reviewed by a civil engineering educator outside the research team to support internal consistency in coding and credibility in the context of civil engineering practice. This process allowed us to mitigate researcher effects, first by including reviewers who are civil engineers but not education researchers, and second by including education researchers (Authors 4 and 5) who are located in a different part of the country and do not have civil engineering backgrounds and provide alternate perspectives to counter site- and field-specific biases. In addition, the iterative coding process enabled us to continually check for outliers, identifying excerpts that did not match the theme definitions and revising the definitions or coding of segments accordingly. Finally, a comparison of these findings to prior research and to ongoing research by Authors 3 and 4 on professional engineering practices in other fields helped confirm external credibility.

Notably, while the data collected could be applicable to other engineering disciplines and the perceptions of professional civil engineers in other regions, it is important to note the limitations of the dataset. Only civil engineers were interviewed; therefore, perspectives of other engineering disciplines, such as mechanical and electrical, may have different skills that are developed throughout a career. Furthermore, all of the participants worked in the same region of the Pacific Northwest. Engineering practice may look different in other regions of the United States, as well as in other countries with different cultures and formal education. In addition, while we identify trends by career phase, the number of participants in each phase is small, and these trends are exploratory only. While they may be broadly applicable, a larger sample is needed to support these initial findings. None of the participants worked for government agencies, where career phases and responsibilities may be different from consulting practice.

Findings

One of the key findings from this study is the complex array of knowledge and skills participants reported learning throughout their careers. In particular, while thematic analysis allowed us to group the knowledge and skills into larger generalized themes, the detailed codes offer a more concrete explication of each theme as it emerged among the civil engineers who participated in this study than found in previous work. As a result, we present our findings as preliminary taxonomy of lifelong learning in civil engineering that can guide both educational practice and future research. Table 3 summarizes the operational definitions and subcodes for each theme. The first four themes focus on skills and knowledge (RQ1), while the last theme addresses how learning happened (RQ2). The following sections define each theme and its subcodes in detail, followed by a discussion of how patterns change across career phases and trajectories. Note that because of the number of codes in each theme, we have not included representative quotations in the text; instead, this information appears in Appendixes I–V.

Skills and Knowledge Learned, Improved, or Mastered

Technical Skills and Knowledge

Almost all participants discussed the need to learn technical skills. Most of the conversation was about the importance of technical skills for engineering practice, especially in regard to entry-level engineers who perform a majority of the day-to-day design and analysis tasks. This theme includes five subcodes.

Design. Nearly all participants (17/19) mentioned "design" when responding to prompts about what technical skills need the most development. Probes to define what constitutes "design" in the context of civil engineering practice indicated that participants were referring to the skills needed to create an actionable plan to solve the problem they were given. For participants in a structural engineering firm, design may be the sizing and drawings of a posttensioned floor slab for a building. For participants in a civil engineering firm, design may be grading and site preparation plans to prepare for the construction of a new piece of infrastructure. When discussing on-the-job learning, participants focused on developing the skills needed to apply the generalized domain knowledge learning in school to specific contexts. That is, participants did not lack basic design knowledge (with the exception of seismic design, discussed later) but lacked the skills needed to apply that knowledge in specific contexts.

Software Skills. Approximately 58% of the participants (11/19) cited the need for software skills to be efficient in the professional environment. These included general software skills related to common office needs, such as email and word processors. But they also included a broad range of engineering- and civil engineering-specific technical software programs used frequently. The purpose and utility of software programs varied widely and sometimes were company specific. Entry-level and senior engineers can routinely use up to ten different technical software programs in a given work week, which might assist them in completing different types of calculations, drawings, or site/system-specific analyses. The breadth of software participants mentioned implies that formal undergraduate education cannot prepare students with all the necessary software skills they may need in practice. Rather, students need to learn how to learn new software and, within civil engineering, how to use and validate technical models with software as well as what core concepts underlie technical analyses.

Fundamental Knowledge. Fundamental knowledge was defined by the participants as the core concepts and principles that constitute structural engineering practice including but not limited to those found in introductory undergraduate statics, mechanics of materials, and dynamics courses, as well as those included in upper-level and graduate-level courses such as structural analysis, structural stability, structural dynamics, and numerical-modeling techniques. As with design, however, participants identified the need to learn fundamental knowledge in school and then develop the skills needed to apply that knowledge to a wide range of contexts.

Codes and Specifications. The need to understand and apply all relevant federal, state, local, and material-specific codes and specifications emerged frequently due to the extensive regulations that govern civil engineering projects. While most formal education curricula expose students to codes and specifications at a general level, participants noted that practice required both familiarity with far more codes and specifications than they had learned in school and a much deeper understanding of all the regulations within each code or specification document.

Seismic Design. Not surprisingly given the high seismic risk of the geographic bounds of our study, many of the engineers interviewed (8/19) mentioned the steep learning curve associated with the skills and knowledge surrounding seismic design in particular. Seismic design is region-specific, complex, and can affect every aspect of a project's design in locations subject to high seismic hazards. Therefore, many participants explained that they had not even been introduced to seismic design in their undergraduate education and instead only learned it after starting as an entry-level engineer.

Project Review. Reviewing projects is an essential task in the engineering office and ensures projects are achieving their intended purpose and that they are safe for the public. The skill of project review is only possible when engineers have mastered the technical knowledge needed on a project, enabling them to no longer need to do all the detailed calculations to be able to decern as to whether the answer is acceptable.

Communication Skills

Communication was a dominant theme, with participants ranging from an entry-level engineer with only a year of experience to a vice president with 40 years of experience citing it as the primary skill for success.

General Communication. The most frequent discussion of communication during the interviews was general, with 84% of the participants (16/19) often not distinguishing between the mediums (i.e., oral, written, visual), audiences, or genres. These comments and discussions focused more on the importance of being able to convey ideas about an engineering problem or solution to both technical collaborators and/or nontechnical clients.

Oral Communication. Oral communication was only explicitly discussed by 26% (5/19) of the participants. Oral communication was defined as any verbal discussion occurring during the workday.

Audience Adjustment. Audience adjustment was mentioned by some of the participants (6/19) and was often discussed in the context of removing jargon and technical context when discussing objectives with nontechnical audiences. Project managers and vice presidents discussed this as explaining what role the engineering firm is fulfilling in broad terms, rather than diving into the "weeds" of the specific analyses or design components.

Emails. One of the most frequently used forms of professional written communication cited by participants (11/19) was email. We separated email as a code both because of its prominence and because it receives little if any attention in engineering courses relative to genres such as reports and memos. Our data suggest that it is a primary mode of communication across all the workplaces and position levels in our study.

Other Written Communication. Other genres of written communication, such as memos, requests for information (RFIs), and reports, were discussed by 7 of the 19 participants. Reports are definitively part of every engineering firm's output to clients, so it is interesting that they were discussed so infrequently by participants in the context of the interviews.

Visual Communication. Though cited by the fewest number of participants (4/19), visual communication still emerged as an important dimension of communication that includes the ability to create clear and organized graphics or sketches to present ideas to other engineers or to clients. For civil engineering, visual communication most commonly is referring to drawings, plans, or plots presenting data.

Professional Skills and Knowledge

The third theme encompassed a broad range of knowledge and skills generally treated as "professional" in the literature. The six codes in this theme center around the ability to work well with people to accomplish engineering tasks and build productive working relationships with everyone involved in an engineering project.

Teamwork. Teamwork was discussed as a critical skill requiring continued learning by approximately one-third of the participants (7/19). Projects completed by engineering firms involve collaboration by individuals across a wide range of specialties. Teams also often work with external partners such as architects or contractors. The necessity of active listening and negotiation was frequently discussed by experienced participants as important to promoting a positive team experience. Participants also noted that teamwork in industry moves beyond delegation of tasks—i.e., the "divide and conquer" approach often seen in student teams—and instead is highly collaborative, with multiple teammates working together on the same task or negotiating decisions to consensus across stakeholders.

Leadership. Leadership was also discussed by 7 of the 19 participants as a skill that required continued learning. Not surprisingly, the engineers discussing the importance of leadership skills were often in roles where they were expected to manage groups of engineers.

Client Relationships. At its core, civil engineering is a service industry, meaning that client relationships are paramount to a firm's overall financial stability. Of all the professional skills, client relationships was the most universally discussed skill among the participants (15/19), regardless of career level. While project managers and vice presidents were formally tasked with client relationships as part of their jobs, even entry-level and senior engineers reported having to build and maintain positive client relations. They all mentioned recognizing the need to further develop interpersonal and networking skills.

Mentoring. Mentoring as a skill was mentioned by 5 of the 19 participants, who were mostly project managers. In the context of the engineering design office, mentoring included a wide variety of practices from providing career advice to showing someone how to complete a specific design or analysis task.

Societal and Cultural Understanding. Some participants (5/19) also noted the need for societal and cultural understanding in relation to teamwork and client relationships. For example, one vice president cited the need to understand the environmental impacts of the construction industry and know how to minimize those impacts because many clients are increasingly aware of carbon emissions issues and are pushing for more sustainable designs. Similarly, understanding local cultures—long recognized as important in international projects—is also becoming an important consideration for domestic projects. One participant, for example, noted the need to understand the history and cultural significance of the local area when making design decisions.

Time Management. Finally, 26% of the participants (5/19) discussed the need for strong time management skills. This skill was mostly discussed by entry-level engineers with less professional experience, possibly suggesting that it is a skill developed most during early-career stages. The early-career engineers discussed how they work on multiple projects at once, meaning they have to balance their workload to meet all their project deadlines.

Business Skills and Knowledge

Business skills and knowledge, though more limited in the data than the other three themes addressing RQ1, still emerged as a distinct theme, particularly among more senior participants. Codes in this theme focus specifically on how the organization itself operates.

Finance. Finances included two different levels. At the highest level, company finances in civil engineering firms are generally handled only by senior management. Because these individuals lead company operations, they are responsible for the firm's financial well-being. On the other hand, project-specific finances, such as managing a budget, are handled by project managers. Because these financial management skills are not commonly taught in civil engineering curricula, some participants mentioned needing additional schooling, such as taking formal business courses or obtaining a Master of Business Administration (MBA) to learn the domain knowledge and associated skills.

Company Operations. Civil engineering firms are complex organizations that rely on a variety of different departments to function together to help develop successful projects. Vice presidents are responsible for overseeing all of the different departments and ensuring that the company is operating efficiently and effectively to meet the demands of the industry, which in turn requires a deep understanding of how the whole company operates and how the pieces work together to ensure profitability. Several of the vice presidents in this study cited the steep learning curve associated with building this understanding.

Overall Vision. Finally, while a deep understanding of both finances and operations was essential for senior leaders, several participants (4/19) also cited the need to understand and build their organization's overall vision. This includes what markets and types of projects the engineering firm should pursue in the future. It also includes forecasting what services they could provide to existing and new clients that will ensure the acquisition of new projects. This skill was mentioned by one of the vice presidents as being important for ensuring the firm remains relevant and can continue to attract work over time.

Learning Methods

As the themes describing what skills and knowledge participants needed to succeed suggest, all participants in this study identified significant learning that occurred on the job. All participants treated lifelong learning as an essential component of practice and considered striving to learn new things and become better at their jobs as central to the engineering ethos. As participants noted, civil engineering programs cannot teach all the knowledge and skills needed for practice, nor can they address the intricacies of specific companies and how each firm prefers to work with its clients. Even when new graduates brought basic skills and fundamental knowledge from school, they still needed to learn to apply those skills to the specific projects and sites of their new firm. Four different learning methods emerged from our data.

Mentorship

Mentorship, in addition to being a needed skill, was also one of the most commonly discussed methods of learning mentioned. Roughly 86% (17/19) of the participants identified learning from another individual as key to their development. Some participants reported formal programs in which the company matched new hires with designated mentors, while others reported relying solely on more informal mentoring that occurred through their design teams.

Related to how mentoring was affecting learning in the design office, when participants were asked how they overcame challenges, a popular response was that they asked questions and sought out a person they thought might be able to help based on previous experience. Being able to ask well-thought-out and specific questions was one of the most emphasized skills by participants. One participant described their approach to asking questions as first attempting to complete the task while keeping a running list of questions before seeking help. This way the questions were specific, could result in quicker answers than broad generalized questions, and could be all answered at once preserving the time commitment of their senior engineer mentor.

Experience

Most (16/19) participants also described learning new skills through experience on the job by working on real projects. Participants strongly emphasized learning through experience as one of the best methods to achieve mastery.

Formal Classes and Presentations

All 19 participants discussed formal classes and/or presentations as a preferred method of learning. Shorter presentations were mentioned by many of the participants as an accessible resource for learning new skills or knowledge, and they were frequently reported as being provided to employees by companies for continued learning. Many of the participants discussed in-house presentations, such as "lunch-and-learns," where the firm had either an internal or external speaker teach a specific topic. Several of the firms also encouraged employees to attend conferences and where numerous presentations could be attended. A few of the companies encourage employees to give presentations about a specific topic. This was mentioned by participants to help the presenter develop a deep conceptual understanding of the topic, while also facilitating a forum for practicing effective communication and public speaking skills.

Self-Directed Study

Finally, while participants learned from others through both formal and informal approaches, they also cited the need to learn on their own (10/19). As practicing engineers, they inevitably faced problems that they did not know how to solve and needed to engage with those problems in a systematic way to find a solution. As one project manager explained, engineers need to "figure out how to figure it out," which described the metacognitive practices associated with self-directed learning—that is, learning that happens outside a formal course structure, in which individuals identify their own learning needs as well as the resources to address those needs and monitor their own progress (Azevedo 2009). For our participants, these

J. Civ. Eng. Educ., 2022, 148(4): 04022007

practices included recognizing the need to continually keep up to date with new developments in the codes and standards, reviewing technical documentation from relevant professional organizations, reading textbooks and journals to understand new analysis techniques, and identifying experts within and outside the company with project-specific knowledge.

Variations in Skills and Learning by Career Phase

While broad views of necessary skills and approaches to learning are valuable, to better inform engineering educators and employers alike, we also analyzed the core themes in light of career trajectory to provide a more nuanced understanding of how the skills, knowledge, and learning approaches change across a career.

First, with respect to technical skills and knowledge, most participants discussed the need for strong skills related to the design and application of codes and standards, and more than half noted the need for software skills, as shown in Fig. 1. All entry-level engineers cited software skills and codes and specifications, and 80% cited design, suggesting that learning in these areas was exceptionally prominent for new engineers. Moreover, even at the vice president level, half of these participants cited the importance of strong technical knowledge regarding the fundamental knowledge underlying design, noting that this fundamental knowledge is the basis for all codes, regulations, and analysis methods. They noted that while codes and methods frequently change over time, the fundamental concepts remain the same and thus serve as useful tools that allow engineers to understand problems holistically, beyond the current set of regulations.

Notably, in reviewing the transcripts, the team also noted that although project managers and vice presidents did not explicitly cite technical skills as frequently as entry-level engineers, these senior-level participants still had the highest level of domain knowledge in their respective offices. That is, although experienced engineers described themselves as less skilled in current technical software, they still made the biggest design choices about site layout, structural system selection, and materials. The centrality of technical expertise is likely tied to the nature of civil engineering practice, where all projects are in some sense unique and dependent on the particular constellation of location, client preferences, site challenges, intended usage, and more. The process of designing unique solutions to different problems requires a wide range of technical skills and a deep understanding of technical concepts to ensure that all projects remain equally safe for the public and useful.

With respect to communication, most participants (84%) cited general communications skills as necessary, as shown in Fig. 2. Entry-level and design engineers primarily communicated

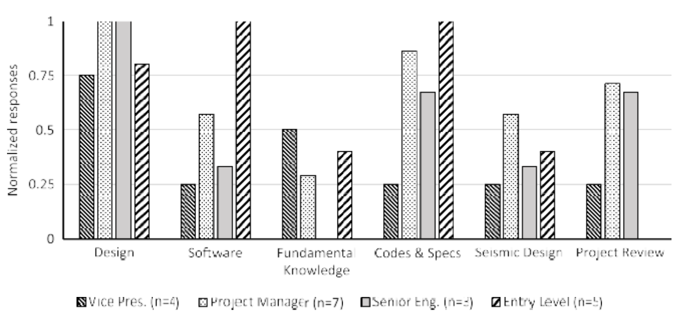

Fig. 1. Participants reporting technical skills and knowledge by career phase.

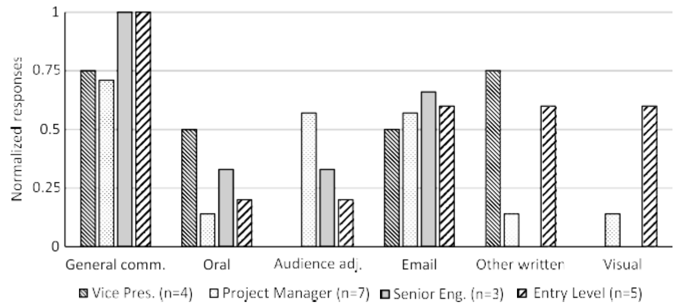

Fig. 2. Participants reporting communication skills by career phase.

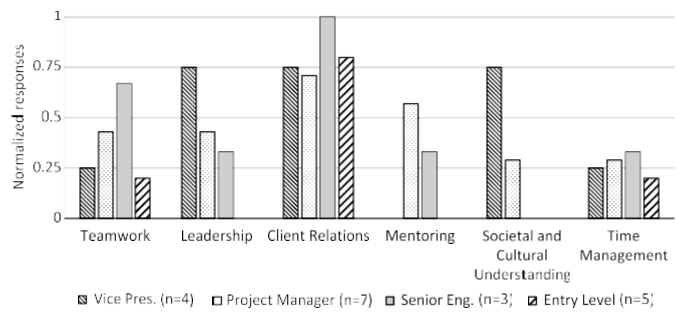

Fig. 3. Participants reporting professional skills by career phase.

internally with project managers and colleagues, with an emphasis on clear written communication, email, and visual communication. Interestingly, entry-level engineers were those most likely to mention visual communication, perhaps because more experienced engineers were less likely to be responsible for the basic tasks requiring drafting software. The trend may also suggest that more experienced engineers were accustomed to reading drawings for information, whereas entry-level engineers had to spend more of their time learning to gather information from visual references. In contrast, project managers and vice presidents most often communicated externally with clients and were more likely to cite oral communication skills, including adjusting to nontechnical audiences.

Professional skills, summarized in Fig. 3, were primarily cited by the project managers and vice presidents. The only exception was client relations, which emerged across all participants. Leadership and social and cultural understanding were discussed primarily by the vice presidents, likely due to their roles in the company. In contrast, client relations, mentoring junior engineers, and project review were most often cited by project managers.

Not surprisingly, business skills, shown in Fig. 4, were mostly discussed by vice presidents, particularly in terms of overall vision and company operations, though one project manager and one entry-level engineer also cited finances. This pattern is consistent with the job responsibilities at these levels.

Finally, trends in learning methods are summarized in Fig. 5. The most frequently discussed modes of learning were mentorship, experience, and formal classes and presentations. However, some skills and knowledge were learned more frequently using certain modes more than others, particularly mentorship and on-the-job experience. Mentorship was discussed as a cornerstone of engineering practice. Almost all participants felt that it was critical to professional success. The skills and knowledge gained or improved through mentorship varied depending on where the individual

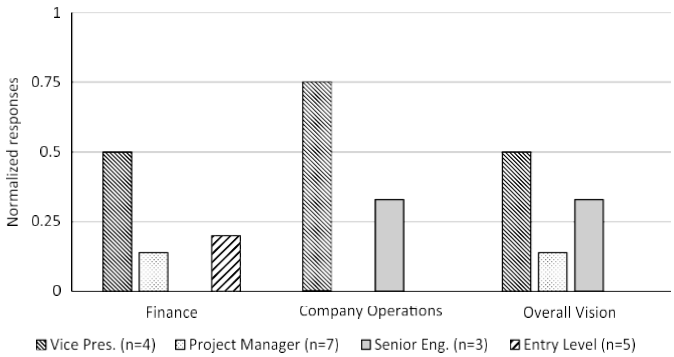

Fig. 4. Participant reporting business skills by career phase.

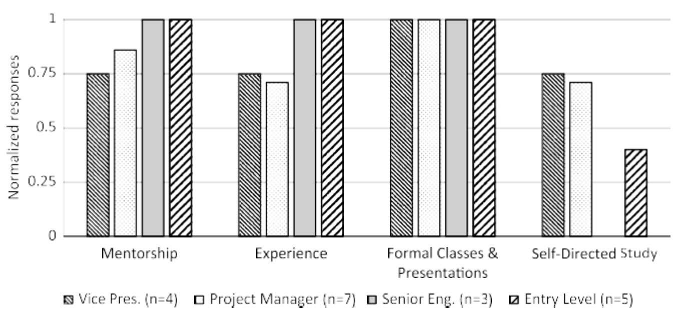

Fig. 5. Participants reporting lifelong learning methods by career phase.

was in their career. Entry-level and senior engineers often relied on mentors for technical tasks, while project managers and vice presidents referred to their mentors as resources for learning professional and business skills. Presentations and self-directed study were discussed mostly in relation to improving technical and communication knowledge. Therefore, the distinguishing characteristic of what learning mode was used was whether the participant was aiming to improve their conceptual understanding of a topic or if they were aiming to gain a new skill. Skills were learned through peer-to-peer or peer-to-mentor interactions and by gaining experience. More formalized learning through presentations and self-directed study were used for improving, or gaining, knowledge in conceptual topics.

Discussion

Findings from this exploratory study of lifelong learning among practicing civil engineers in the Pacific Northwest mirrored several trends seen across other recent studies of professional engineering practice, including the need for communication and teamwork skills (Brunhaver et al. 2018; Ford et al. 2019, 2021). These patterns include trends seen in studies of professional communication outside the engineering education field, including the prominence of email as a primary mode of communication (Knoch et al. 2015; Wisniewski 2018); this issue is particularly important because undergraduate engineering education, including civil engineering, tends to emphasize report genres, with less attention to the importance of email as a medium for sharing a wide range of information. Similarly, these findings emphasize the importance of communicating and collaborating with external audiences, including clients generally, for civil engineers, in particular, in fields such as architecture and contractors.

The findings also stress the centrality of self-directed learning, learning through individual interactions (mentorship and asking questions), and learning through experience (Korte 2019; Korte 2009; Lutz and Paretti 2017; Paretti et al. 2020). As these studies emphasize, while some learning occurs through formal courses and presentations that may parallel the school environment, learning at work depends heavily on interpersonal relationships, asking questions, and developing relationships with mentors—again, practices that may not be uniformly developed in undergraduate programs. Our findings, for example, echo recent research on new engineers' transition to work and highlight the critical nature of self-directed learning for early-career engineers in particular as they move from the structured, classroom-based learning environment of the school to the informal, networked learning environment at work (Paretti et al. 2020).

At the same time, the findings also begin to fill the research gap identified by Mazzurco et al. (2021) relative to learning within specific disciplines and industries. In doing so, they provide a detailed taxonomy of the knowledge and skills practicing civil engineers report learning that extends previous work. When taken as a whole, the findings also illustrate the complex and diverse learning that continues well beyond the end of an undergraduate or even graduate degree. Within and across career phases, the participants in our study continued to build a wide range of technical, communicative, professional, and business skills and knowledge over the course of their careers, with different skills salient at different points.

Our study identified, for example, that within civil engineering, codes and specifications play a critical role in practice, and also reinforced the need for a deep understanding of fundamental technical principles that undergird the continually evolving regulations. In particular, our participants referenced codes for materials or design loads, such as reinforced concrete, seismic, and wind, that are likely discipline-specific, though as noted earlier, other engineering fields may have different—and different kinds—of regulations that shape their work. Understanding both the kinds of regulations (e.g., local building codes such as those seen in our study) that govern work within different engineering fields and how those regulations change over time can and should inform how we teach technical and design skills in undergraduate degrees. Within civil engineering, for example, rapid changes in the industry on materials used during construction (e.g., increasing use of mass timber) or software used for certain analyses combined with relatively slowly evolving prescriptive design codes reinforces the need for students to understand both fundamental concepts of design for static, dynamic, and hydraulic loading and the current code-based procedures. The importance of conceptual understanding is not itself new, of course, nor is it unique to civil engineering (Streveler et al. 2008). Instead, what we suggest here is that understanding how conceptual understanding emerges in practice—here, in the context of responding to changes in design codes—can help educators both motivate student learning and better prepare them to adapt current knowledge to future practice. Recent work by Bornasal et al. (2018), for example, on conceptual knowledge in civil engineering practice is particularly salient to this goal.

Similarly, our study also highlights the kinds of location-specific technical knowledge civil engineers need to acquire. In this case, for engineers practicing in the Pacific Northwest, seismic design plays a key role. That is, the necessary technical knowledge can be industry-specific (e.g., types of structures) and location-specific. The nature of the work also plays a key role in the kinds of contextual knowledge participants will need to learn.

J. Civ. Eng. Educ., 2022, 148(4): 04022007

While accreditation criteria call for engineers to consider "the impact of engineering solutions in global, economic, environmental, and societal contexts" (ABET 2018), graduating civil engineers need to be prepared to develop particular kinds of knowledge and understanding when they enter the workplace. Specifically, participants in this study highlighted the need to understand the environmental and impacts of infrastructure projects and to identify ways to minimize those impacts. At the same time, they also need to be able to identify and analyze the historical and cultural significance of the sites where projects are planned and incorporate that understanding into designs. Mining engineers, for example, might need similar kinds of location-specific knowledge, but mechanical engineers entering into manufacturing industries may instead need to be prepared to develop industry- and product-specific knowledge rather than location-specific understandings. Future work on lifelong learning in other disciplines is needed to deepen our understanding of these issues.

The nature of the industry also shapes some dimensions of the kinds of interpersonal skills engineers need. For example, it is not surprising that client relations were important among entry-level engineers, even when client management was not a formal part of their job duties. At the same time, although many of the current industry reports highlight new engineers' need for business acumen (ASME 2013; American Society of Mechanical Engineers Center for Education 2011; National Academy of Engineering 2004), skills and knowledge related to finance, and business operations emerged predominantly for the more senior engineers in this study; undergraduate civil engineering students may require a different level and kind of exposure to these issues than, for example, students in industrial and systems engineering where business skills may be highly salient much earlier in their careers. Yet, the more senior engineers in our study also continued to engage deep technical expertise in making and approving major design decisions across projects.

Conclusion and Implications

Through semistructured interviews with 19 civil engineering practitioners in the Pacific Northwest, this exploratory study addressed three research questions: (1) what skills and knowledge are required, learned, or improved during a civil engineering career, (2) how do practicing civil engineers engage in learning, or further improving, skills and knowledge, and (3) how do these skills, knowledge, and learning practices vary across career phases. The analysis identified four themes related to skills and knowledge (technical skills and knowledge, communication skills, professional skills and knowledge, and business skills and knowledge), with a detailed taxonomy for each theme, along with four primary modes of learning. The results suggest several key directions for civil engineering educators.

First, technical knowledge and skills, including both design and fundamental concepts (including those from advanced courses), remain central to practice and are also tied closely to the application of relevant codes and regulations. Yet, the emergence of location-specific skills (seismic design in this study) also suggests that new engineers will have to build significant technical skills relative to their firm's project locations. Given the wide range of environmental hazards present in different locations, undergraduate programs are unlikely to be able to provide robust location-specific technical skills with the depth that engineering practice requires. Employers, on the other hand, may want to consider specific learning opportunities, such as short courses or workshops, that address such skills. Similarly, the kinds of software packages as well as the codes and specifications that engineers in this study needed varied widely (and change regularly), making it impossible for undergraduate programs to cover them all. Instead, curricula should continue to focus on the conceptual domain knowledge that undergirds these programs and regulations while at the same time highlighting best practices for learning new software programs and processes for validating program outputs using engineering principles.

Second, and not surprisingly, communication remains a critical skill for practice (e.g., Sripala and Praveen 2011; Brunhaver et al. 2018; Redoli et al. 2013; Sripala and Praveen 2011; Pence and Rowe 2012; Ford et al. 2019, 2021). Perhaps most notably, this study echoed findings from outside engineering education research on the importance of email as the most frequent form of written communication both internally and externally with clients, subcontractors, and regulators. As a result, faculty should consider incorporating more formal attention to this mode of communication, with specific attention to the audiences relevant to civil engineering practice, as students communicate with each other and with course instructors on project work. In many ways, course management systems, where students submit assignments through a web portal, and informal communication channels such as Slack, GroupMe, or WhatsApp, have replaced email within the university. Some of these channels have begun to permeate workplaces, particularly since the COVID-19 pandemic (e.g., Slack for internal communication), but email remains a dominant technology and faculty should reconsider its role in undergraduate courses.

Finally, given the prominence of informal learning, undergraduate programs should consider increasing the emphasis on metacognitive activities that encourage students to analyze and reflect on the learning techniques that work for them. Findings and resources from the Skillful Learning project in engineering education may be particularly useful here (Cunningham et al. 2021, 2015), as might the significant body of work on helping students develop effective questioning skills (Chin and Osborne 2008; Graesser et al. 1992; King 1991; Rosenshine et al. 1996). Furthermore, curricular changes to increase students' ability in LLL engagement have been done in past studies (e.g., Bondehagen et al. 2014; Peat et al. 2005; Stolk and Martello 2015). The interview data also point toward experience and peer-mentorship being two of the main methods of learning, supporting the benefits of capstone courses that emphasize teamwork, team learning, and problems with a larger scope. Previous research on capstone projects (e.g., Paretti et al. 2020; Steiner et al. 2015) highlights the ways these projects can support self-directed learning and provide students with opportunities to apply both professional and technical skills. At the same time, concepts from capstone courses should be implemented earlier throughout the curriculum where appropriate to further develop the skills of self-directed learning, teamwork, communication, the ability to teach others, and the ability to ask productive questions. Given that mentors also benefit from such interactions, (e.g., Linte 2015; Stewart and Harrison 2016), peer mentoring approaches could benefit all students involved.

Learning, as our participants made clear, happens continually in multiple modes through a civil engineering career and encompasses a wide range of technical and professional practices. As undergraduate programs seek to better prepare new graduates for work and employers seek to effectively onboard new hires and support career growth, detailed studies of learning at work are essential. This study provides a key contribution to such knowledge for the profession and lays the groundwork for additional research both within civil engineering and across other engineering disciplines to further build our understanding.

Appendix I. Representative Quotes from the Interview Transcripts for Each of the Research Codes: Technical Skills and Knowledge

Code	Representative quote
Design	"*What we get paid to do is provide a technical service that nobody else could do ::: you're going to hire a structural engineer because you need to know, specifically, and you need someone to do the physics to show that this particular thing will work*"—(Senior engineer)
Software skills	"*That is definitely a big pick up, because in college you only scratch the surface of the programs that you're supposed to be using. So like, for me, Civil3D [a civil engineering design software] and picking that up was a big learning curve for me. As of anyone who comes into a new civil [engineering] position*"—(Senior engineer)
Fundamental knowledge	"*It all does come down to the fundamentals that you do learn in school, but obviously you have to learn how to manipulate what you did learn in school to make it work for whatever it is that you're doing that's atypical*" —(Entry-level engineer)
Codes and specifications	"*Knowing what part of the codes you need to go to/what codes you need to follow. I feel like that's pretty important.*"—(Entry-level engineer)
Seismic design	"*Just understanding how much there really is that goes into these seismic designs that you don't necessarily learn about in school*" —(Entry-level engineer)
Project review	"*Where I'm at right now, I'm checking calculations that other engineers have already performed, and so I'm not necessarily doing the calculations from scratch*"—(Project manager)

Appendix II: Representative Quotes from the Interview Transcripts for Each of the Research Codes: Communication Skills

Code	Representative quote
General communication	"*One, communication. Engineers need to know how to communicate what it is they're doing*" (Vice president)
Oral communication	"*That communication and being willing to talk to people, because sometimes, like I'm introverted, you want to go and you sit in your little cubicle sometimes. And oh, just let me do calculations. But no, you're going to have to talk to people*"—(Project manager)
Audience adjustment	"*Knowing the audience and communicating clearly with them is really key*" —(Project manager)
Email	"*Well typically my day starts even before I get to work, now that email can reach me anywhere on my phone and most of my projects are not here in this time zone. I wake up to a ton of emails*"—(Senior engineer)
Other written communication	"*Communication. I mean it's incredibly important to be able to communicate in writing and so writing skills, which I never thought were going to be important, even early on became very important*"—(Vice president)
Visual communication	"*I think a lot of people don't want to spend a lot of time making their things look nice. Then when you go to say you have a question about a graph that you want to go show somebody, and it is a big mess, it's really hard to present your results and talk clearly with somebody unless you've made it look nice and spent the time to like organize your thoughts in that way*" —(Entry-level engineer)

Appendix III: Representative Quotes from the Interview Transcripts for Each of the Research Codes: Professional Skills and Knowledge

Code	Representative quote
Teamwork	"*You got to take the journey together sometimes on these decisions with the team, make sure everyone feels like they have a say in it. So when you do come to that answer, everyone's feeling as good as hopefully they can*"—(Project manager)
Leadership	"*A lot of people would say leadership is driving, right? I would say that leadership is guiding with a clear direction. And building a team to support that direction*"—(Vice president)
Client relationships	"*And so you learn the relationship side of business, that people don't give you business because they like how pretty your sign is out front, it's a relationship. So, people come to you, particularly in professional services, they come to you because there's a relationship and they trust you*"—(Vice president)
Mentoring	"*It's one thing to do it, it's another thing to teach somebody and I think you learn way more teaching*"—*(Project manager)*
Societal and cultural understanding	"*The time change, culture, sometimes the language ::: The construction sophistication there is not the same as in the US, so you have to be a little more careful with what types of systems you propose. They just don't have as highly skilled labor, so you have to be careful. In some cases the codes are different than the US, so we got to learn how to use the international codes ::: Politics. Being the foreigner, you have to be careful with politics and who you work with and who you try to be on their good side with*"—(Project manager)
Time management	"*Learning how to balance several jobs at the same time because we might be working on six or seven different projects at once. And so just kind of balancing that out throughout the week and getting done what you need to get done*"—(Entry-level engineer)

J. Civ. Eng. Educ., 2022, 148(4): 04022007

Appendix IV: Representative Quotes from the Interview Transcripts for Each of the Research Codes: Business Skills and Knowledge

Code	Representative quote
Finances	"*We're a for-profit company so we want to actually make some money. It's not our job to lose money. We wouldn't be in business very long*"—(Vice president)
Company operations	"*If you look at the engineering consulting business, the actual technical design is probably 25% of the business. Whereas you have everything else associated with finance, economics, management of projects, the systems, the business development, the marketing, research. I mean there's so many other things that sit within that consulting profile*"—(Vice president)
Overall vision	"*Being able to react to the clients and their demands is the most challenging thing that I face on a regular basis. We do a lot of work for [Company] and [Company] and the science and technology industry, and they evolve so quickly that you have to evolve with them or else you lose the value and credibility, associated with making their projects a success and what they want to do with their projects.*"—(Vice president)

Appendix V. Representative Quotes from the Interview Transcripts for Each of the Research Codes: Learning Methods

Code	Representative quote
Mentorship	"*When I started, I was assigned a peer mentor. So any ::: they call them stupid questions, that you have, that's the person you ask*"—(Entry-level engineer)
Experience	"*I mean a lot of times it's doing things, actually doing it. A lot of times you learn best from having to sit and figure it out on your own, even though you've got these resources over here that can help you*"—(Project manager)
Formal classes and presentation	"*We try to have lunch and learns or different things where we're bringing in maybe people outside the company to come share product information or things like that. Or, you know, we have somebody present on a project they're working on, the lessons learned from it, that type of thing*"—(Senior engineer)
Self-study	"*I think the next skill set is being able to continue to educate yourself on those other aspects because you cannot be an expert at all things. So you got to rely on documentation, data, research, that you actively go and look and read and understand*"—(Vice president)

Appendix VI: Quantitative Data from Frequency of Participant Responses Used to Create Fig. 1 on Technical Skills and Knowledge by Career Phase

Career phase	Design	Software skills	Fundamental knowledge	Codes and specs	Seismic design	Project review
Total (*n* ¼ 19)	90% (17)	58% (11)	32% (6)	74% (14)	42% (8)	42% (8)
Vice president (*n* ¼ 4)	75% (3)	25% (1)	50% (2)	25% (1)	25% (1)	25% (1)
Project manager (*n* ¼ 7)	100% (7)	57% (4)	29% (2)	86% (6)	57% (4)	71% (5)
Senior engineer (*n* ¼ 3)	100% (3)	33% (1)	0% (0)	67% (2)	33% (1)	67% (2)
Entry level (*n* ¼ 5)	80% (4)	100% (5)	40% (2)	100% (5)	40% (2)	0% (0)

Appendix VII: Quantitative Data from Frequency of Participant Responses Used to Create Fig. 2 on Communication Skills by Career Phase

Career phase	General communication	Oral	Audience adjustment	Email	Other written	Visual
Total (*n* =19)	84% (16)	26% (5)	32% (6)	11 (58%)	37% (7)	21% (4)
Vice president (*n* ¼ 4)	75% (3)	50% (2)	0% (0)	50% (2)	75% (3)	0% (0)
Project manager (*n* ¼ 7)	71% (5)	14% (1)	57% (4)	57% (4)	14% (1)	14% (1)
Senior engineer (*n* ¼ 3)	100% (3)	33% (1)	33% (1)	66% (2)	0% (0)	0% (0)
Entry level (*n* ¼ 5)	100% (5)	20% (1)	20% (1)	60% (3)	60% (3)	60% (3)

Appendix VIII: Quantitative Data from Frequency of Participant Responses Used to Create Fig. 3 on Professional Skills and Knowledge by Career Phase

Career phase	Teamwork	Leadership	Client relations	Mentoring	Societal and cultural understanding	Time management
Total (*n* =19)	37% (7)	37% (7)	79% (15)	26% (5)	26% (5)	26% (5)
Vice president (*n* ¼ 4)	25% (1)	75% (3)	75% (3)	0% (0)	75% (3)	25% (1)
Project manager (*n* ¼ 7)	43% (3)	43% (3)	71% (5)	57% (4)	29% (2)	29% (2)
Senior engineer (*n* ¼ 3)	67% (2)	33% (1)	100% (3)	33% (1)	0% (0)	33% (1)
Entry level (*n* ¼ 5)	20% (1)	0% (0)	80% (4)	0% (0)	0% (0)	20% (1)

J. Civ. Eng. Educ., 2022, 148(4): 04022007

Appendix IX: Quantitative Data from Frequency of Participant Responses Used to Create Fig. 3 on Business Skills and Knowledge by Career Phase

Career phase	Finance	Company operations	Overall vision
Total (*n* =19)	21% (4)	21% (4)	21% (4)
Vice president (*n* ¼ 4)	50% (2)	75% (3)	50% (2)
Project manager (*n* ¼ 7)	14% (1)	0% (0)	14% (1)
Senior engineer (*n* ¼ 3)	0% (0)	33% (1)	33% (1)
Entry level (*n* ¼ 5)	20% (1)	0% (0)	0% (0)

Appendix X. Quantitative Data from Frequency of Participant Responses Used to Create Fig. 5 on Learning Methods by Career Phase

Career phase	Mentorship	Experience	Formal classes and presentations	Self-directed study
Total (*n* =19)	89% (17)	84% (16)	100% (19)	53% (10)
Vice president (*n* ¼ 4)	75% (3)	75% (3)	100% (4)	75% (3)
Project manager (*n* ¼ 7)	86% (5)	71% (5)	100% (7)	71% (5)
Senior engineer (*n* ¼ 3)	100% (3)	100% (3)	100% (3)	0% (0)
Entry level (*n* ¼ 5)	100% (5)	100% (5)	100% (5)	40% (2)

Data Availability Statement

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request. Items that can be requested are the anonymized interview transcriptions.

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