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*Main Article:*

# Cognitive Apprenticeship and the Supervision of Science and Engineering Research Assistants

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## Abstract

We explore and critically reflect on the research development of eight science or engineering doctoral students serving as research assistants over the course of an academic year. We use a cognitive apprenticeship framework, assumed to explain doctoral students' skill development, to interpret narratives of skill development for students and their faculty supervisors, and compare these narratives against empirical measurements of student research skill development over the course of an academic year. We found abundant evidence for the "cognitive" component of cognitive apprenticeship, but questionable evidence for the "apprenticeship" component. We suggest that cognitive apprenticeship can be particularly potent in the development of students' research skills through research assistantship, but not without deliberate intention of both faculty supervisor and student.

**Index Terms:** research training; research supervision; researcher assistant; researcher development; cognitive apprenticeship

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## 1. Introduction

Increasingly, doctoral degree recipients are seen as "advanced knowledge workers" (Lee & Boud, 2008, p. 18) who must be prepared upon graduation to join a competitive and complex global workplace. Thus, it is not surprising that the preparation of doctoral students as disciplinary researchers has attracted increased scrutiny across a range of stakeholders (Cumming, 2010; Mowbray & Halse, 2010; Pearson & Brew, 2002). It is troubling, therefore, that despite a growing literature base on doctoral student experiences, the ways students actually acquire disciplinary research skills, characterized by Austin and McDaniels as "at the heart of doctoral study" (2006, p. 424), remains understudied (Flores, 2011; Walker, Golde, Bueschel, Jones, & Hutchins, 2008).

Extensive literature asserts the primary importance of the faculty supervisor (the terms *faculty* and *professor* are used here to mean academic staff in general) in students' development as disciplinary researchers (e.g., Nettles & Millett, 2006; Parry, 2007; Wisker, 2005). Much of this literature employs a cognitive apprenticeship framework (e.g., Austin, 2009; Flores, 2011; Parry, 2007; Pearson & Brew, 2002; Walker et al., 2008). Within this framework, the "master" (faculty supervisor) and novice "apprentice" (student) work closely in a one-to-one relationship. Collins, Brown, and Holum (1991) noted that this master-apprentice guidance includes several types of interaction. Specifically, the master *models* or demonstrates the intended processes and makes his or her thinking visible. Austin (2009) added, "The modeling needs to reveal the procedures as well as the 'tricks of the trade' or techniques used in accomplishing the work" (p. 176). The master observes and *coaches* the apprentice as he or she performs the process, providing feedback along the way, and *scaffolds* the apprentice's efforts, "helping the student move to doing increasingly more difficult parts of the work" (Austin, p. 176). As the task difficulty increases, the master encourages the apprentice to articulate and reflect on his or her cognitive processes and practices and invites the student to explore and solve new problems. Finally, the master encourages the *transfer of learning* to a range of situations.

Faculty supervisors may not be the only persons who act as "masters" in the acquisition of research skills, especially for students serving as science and engineering research assistants. These assistantships are often made possible through the award of external research funding. Commonly, the aim and scope of the funded science and engineering projects support the creation of laboratory-based research teams (Cumming, 2009; Parry,

2007) within which research assistantships are embedded. These teams typically include the lead faculty supervisor and possibly other associated faculty, postdoctoral fellows, doctoral students, master's-level students, and sometimes undergraduate researchers. Thus, these teams include members with differing levels of expertise around a common area of investigation and might be considered a community of research practice (Lave & Wenger, 1991). Additionally, varied supervision available within these teams may respond to calls for doctoral mentoring to be spread among multiple relationships to accommodate the multifaceted, integrative learning expected of current doctoral students (Walker et al., 2008).

However, the role of cognitive apprenticeship in the development of science and engineering students as disciplinary researchers perhaps deserves reconsideration. Heightened expectations for scholarly productivity have accelerated the pace of academic work (Austin & McDaniels, 2006; McAlpine & Amundsen, 2011; Peters & Olssen, 2005) with faculty time becoming an ever-scarcer resource (Remler & Pema, 2009). Thus, faculty supervisors may not be able to provide the close attention to individual student development that the cognitive apprenticeship model suggests. Further, because research skills develop over time (Timmerman, Feldon, Maher, Strickland, & Gilmore, 2013), it is possible that students in their first years of doctoral training may not be at a point where their skills capture their faculty supervisors' attention within a fast-paced team environment. Additionally, within the "ever-changing wave of students and postdocs" (Knorr-Cetina, 1999, p. 225) typical of these teams, guidance supplementary to that provided to the new student by the doctoral supervisor might be sporadic at best.

In this study, we explore the development of eight students as disciplinary researchers, as they navigated their first year of doctoral education in a research-intensive US university. Students pursued a doctorate in either science or engineering, and as is common in these disciplines, each served as a supervised research assistant. We paired students' narrative descriptions of research development with that of their faculty supervisor, and then considered both narratives within the context of ratings of student research proposals collected at the beginning and end of their first year of doctoral study. The purpose of our study is to explore the extent to which the cognitive apprenticeship model appears to underlie students' research skill development.

## 2. Participants

We selected participants from a larger project examining the impacts of science, technology, engineering, and mathematics (STEM) graduate students' teaching and research experiences on research skill development (Feldon et al., 2011). The larger study included students who served as research assistants at various stages of their graduate career. For this effort, however, we focus only on research assistants in the first year of their doctoral tenure, as this time period may arguably be most critical in the establishment of a strong intellectual and cultural foundation (Boyle & Boice, 1998). As Golde (1998) observed, in science doctoral education, it is important for students to incorporate themselves successfully into ongoing faculty research efforts, a connection that usually happens within the first year. Additionally, each research assistant was

enrolled full time in a science or engineering doctoral program at a large research-intensive university (Carnegie Classification RU/VH, formerly known as "R1") in the southeastern United States (Carnegie Foundation, 2013). Table 1 displays the pseudonym, gender, native English speaker designation, and program of study for each research assistant.

Table 1. *Research Assistant Demographic Information*

| Pseudonym | Gender | Native English Speaker | Program of Study |
|---|---|---|---|
| "Li" | Male | No | Biology |
| "Kate" | Female | Yes | Epidemiology & Biostatistics |
| "Antonio" | Male | No | Civil Engineering |
| "Lin" | Female | No | Chemistry |
| "Samir" | Male | No | Biomedical Sciences |
| "Jin" | Male | No | Marine Science |
| "John" | Male | Yes | Biology |
| "Alex" | Male | Yes | Biology |

## 3. Instruments, Data Collection, and Analytical Procedures

Data informing this study were collected through the use of two instruments: semi-structured interviews and written research proposals. Semi-structured interviews were conducted in the spring with research assistants and their faculty supervisors. Research assistants described their research experiences over the past academic year, self-perceived changes in research skills, and the nature of their relationship with their faculty supervisor. Key interview questions included, "Describe the research you've conducted since September"; "Did you have much control over the topic, design, and/or implementation of this research?"; "How have your research skills changed since September?"; "What research experiences have helped you become a better researcher since September?"; and "Tell me about your relationship with your faculty supervisor." Faculty supervisors described their working relationship with their assistant, their involvement with their assistant's research efforts in the past academic year, as well as their assistant's research strengths and weaknesses. Interviews lasted approximately 45 minutes, and each was tape-recorded and transcribed verbatim.

The first and second author conducted and transcribed the majority of interviews, thus beginning the analysis process. Conducting interviews allowed personal interactions with the participants, facilitating deeper understanding of interview responses. Similarly, transcribing "is not an antecedent to analysis, but it is a central aspect of the ways that researchers analytically orientate to data" (Gibson & Brown, 2009, p. 125). We used the constant comparison approach (Glaser, 1965) to identify themes in supervisor and student narratives, constantly comparing and contrasting emergent themes both within and across transcripts. Defining interactions of the practice of cognitive apprenticeship (i.e., modeling, coaching, scaffolding, etc.) were noted, as were instances of supervisor-student

agreement and disagreement in descriptions of research activities and development. We then considered qualitative analyses within the context of student research proposal ratings.

We acknowledge that our interpretation of these data was undertaken through the lens of our multiple roles as current and past doctoral students and, for the first three authors, as current doctoral supervisors. Thus, we acknowledge that our consideration of these data and, more broadly, the framing of this study were influenced by both our personal experiences with, and expectations for, doctoral education practices. This is a position of strength in that we are each personally and professionally invested in doctoral education processes and outcomes and, by extension, in the fundamental questions posed by this study. Concurrently, we also recognize this as a position of weakness that may undermine our ability to remain unbiased toward emergent findings contradicting our beliefs about what should or does occur between doctoral supervisors and students. We believe our ability to triangulate our interpretations across data sources may ameliorate some of this tendency toward bias.

In early fall, research assistants submitted research proposals on a topic related to their academic specialization. We encouraged them to conceptualize this effort as a dissertation draft, comprehensive exam proposal, or other real-world purpose so that the work would not be solely for the purposes of this study. Prior to submission, we instructed research assistants to describe the relevant literature and design for their proposed research, their anticipated results, and the significance of results. Research assistants then revised these proposals over the course of the academic year and resubmitted them in late spring as part of their participation in the larger study. We provided no feedback to participants between the fall and spring submissions, though they were free to seek feedback from their faculty supervisor and others as they saw fit.

To evaluate the proposals, four researchers used a rubric that has been validated several times with various populations. Comprehensive validation information pertinent to the current study was reported by Feldon et al. (2011), with intraclass correlations between 0.6 and 0.9 for initial ratings with discrepancies being resolved through discussion thereafter. Extensive treatment of content validation linking aspects of student writing to scientific reasoning can be found in Timmerman, Strickland, Johnson, and Payne (2011). These aspects are briefly stated below to provide an overview, but for a more in-depth treatment we encourage readers to consult Feldon et al. (2011) and Timmerman et al. (2011).

The rubric included 10 research skill criteria: (i) context set for a study, (ii) testable hypotheses framed, (iii) attention to validity and reliability of methods, (iv) experimental design, (v) appropriate selection of data for analysis, (vi) presentation of data, (vii) data analysis, (viii) conclusions based on data, (ix) limitations identified, and (x) effective use of primary literature. These criteria were selected through a review of relevant literature and iterative development of criteria with STEM research faculty. At least two raters with relevant degrees in STEM disciplines scored each proposal. Raters had no contact with research assistant participants outside the context of the larger project. Research

proposals were not blinded and generally, researchers scored the same participants' proposals in the fall and spring. Fall proposals were scored in October and spring proposals were scored in the early summer. Performance was assessed for each rubric criteria using a three-point scale (proficient = 3, intermediate = 2, novice = 1). A plus or minus represents an addition or subtraction of 0.25 from the base (e.g. 1- = 0.75; 0+ = 0.25). Any discrepant scores were resolved by discussion until consensus was reached (for a comprehensive description of rubric design, use, and validation, see Feldon et al., 2011). Table 2 displays research assistants' fall and spring proposal rating scores across the rubric subscales. Occurrence of very high fall proposal scores, which would in turn negate meaningful change in spring proposal scores (i.e., "ceiling effects") are noticeably rare in these data, as might be expected in data secured from early-career doctoral students.

Although the rubric used to assess research skill development delineates specific subscales that formed the basis of the change scores, research assistants described their research skills more broadly during the interviews. Respondents often discussed their areas of growth as encompassing their abilities to communicate their research, operate specific laboratory equipment, implement established research protocols, or "think critically" in a generic sense. These descriptions often either incorporated elements from multiple rubric subscales (e.g., implementing a new protocol can entail attention to issues of reliability, selection of data, data analysis, and use of primary literature) or addressed facets not included in the rubric (e.g., operation of equipment). Thus, the change scores provided a useful guide for the selection of informative cases and the types of skill in which change was demonstrated, but the specific skills delineated in the rubric did not constrain the broader consideration of skills as conceptualized by the doctoral students or supervising faculty themselves.

Table 2. *Research Assistants' Fall and Spring Proposal Ratings and Change Scores for Rubric Components, Subscales, and Total Scores*

| | | Introduction | | Hypo-thesis | Method | | Results | | | Discussion | | Total Scores |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Context | Primary Literature | Hypothesis | Validity and Reliability | Experimental Design | Data Selection | Data Presentation | Data Analysis | Conclusion | Limitations | |
| "Li" | Fall | 2.75 | 1.75 | 1.00 | 1.25 | 2.00 | 1.00 | 0.00 | 1.00 | 1.25 | 0.00 | 12.00 |
| | Spring | 3.00 | 3.00 | 1.75 | 2.75 | 2.75 | 2.25 | 2.25 | 2.25 | 2.25 | 2.00 | 24.25 |
| | Change | 0.25 | 1.25 | 0.75 | 1.50 | 0.75 | 1.25 | 2.25 | 1.25 | 1.00 | 2.00 | +12.25 |
| "Kate" | Fall | 1.00 | 1.00 | 0.75 | 0.75 | 1.00 | 1.00 | 1.25 | 0.25 | 1.00 | 0.75 | 8.75 |
| | Spring | 2.75 | 3.00 | 2.00 | 2.00 | 2.00 | 1.25 | 2.25 | 2.00 | 0.75 | 2.25 | 20.25 |
| | Change | 1.75 | 2.00 | 1.25 | 1.25 | 1.00 | 0.25 | 1.00 | 1.75 | -0.25 | 1.50 | +11.50 |
| "Antonio" | Fall | 3.00 | 2.00 | 2.00 | 2.00 | 2.75 | 2.00 | 0.00 | 1.25 | 0.00 | 0.00 | 15.00 |
| | Spring | 2.75 | 2.75 | 2.00 | 2.75 | 2.00 | 2.00 | 2.25 | 2.75 | 1.25 | 0.00 | 20.50 |
| | Change | -0.25 | 0.75 | 0.00 | 0.75 | -0.75 | 0.00 | 2.25 | 1.50 | 1.25 | 0.00 | +5.50 |
| "Lin" | Fall | 0.75 | 2.00 | 0.75 | 0.00 | 0.75 | 0.75 | 1.00 | 0.75 | 0.00 | 0.00 | 6.75 |
| | Spring | 2.75 | 2.25 | 1.00 | 0.75 | 0.75 | 0.75 | 1.75 | 0.75 | 0.00 | 0.00 | 10.75 |
| | Change | 2.00 | 0.25 | 0.25 | 0.75 | 0.00 | 0.00 | 0.75 | 0.00 | 0.00 | 0.00 | +4.00 |
| "Samir" | Fall | 1.00 | 0.75 | 0.75 | 1.00 | 1.25 | 1.75 | 1.00 | 0.75 | 0.00 | 0.75 | 9.00 |
| | Spring | 2.25 | 2.75 | 0.00 | 1.00 | 1.75 | 1.00 | 0.00 | 0.75 | 0.75 | 0.00 | 10.25 |
| | Change | 1.25 | 2.00 | -0.75 | 0.00 | 0.50 | -0.75 | -1.00 | 0.00 | 0.75 | -0.75 | +1.25 |
| "Jin" | Fall | 1.25 | 1.00 | 2.00 | 0.75 | 0.75 | 0.00 | 0.00 | 0.75 | 0.00 | 0.00 | 6.50 |
| | Spring | 1.75 | 1.25 | 1.25 | 0.00 | 0.75 | 1.00 | 0.25 | 0.75 | 0.00 | 0.00 | 7.00 |
| | Change | 0.50 | 0.25 | -0.75 | -0.75 | 0.00 | 1.00 | 0.25 | 0.00 | 0.00 | 0.00 | +0.50 |
| "John" | Fall | 1.00 | 2.00 | 1.75 | 2.00 | 1.75 | 1.75 | 1.75 | 1.00 | 1.00 | 1.25 | 15.25 |
| | Spring | 1.75 | 2.00 | 1.00 | 1.75 | 1.00 | 1.75 | 1.75 | 2.00 | 1.00 | 1.00 | 15.00 |
| | Change | 0.75 | 0.00 | -0.75 | -0.25 | -0.75 | 0.00 | 0.00 | 1.00 | 0.00 | -0.25 | -0.25 |
| "Alex" | Fall | 2.75 | 2.00 | 2.00 | 1.75 | 2.00 | 1.00 | 0.00 | 1.00 | 0.00 | 0.00 | 12.50 |
| | Spring | 2.00 | 1.75 | 1.75 | 1.25 | 2.00 | 0.75 | 0.00 | 1.00 | 0.00 | 0.00 | 10.50 |
| | Change | -0.75 | -0.25 | -0.25 | -0.50 | 0.00 | -0.25 | 0.00 | 0.00 | 0.00 | 0.00 | -2.00 |

## 4. Results: Research Assistant Profiles

We combine interview analyses and notable proposal rating changes to profile each research assistant's development as a disciplinary researcher.

### 4.1. Li's Profile

Li, who earned a master's degree in biology in China before beginning his doctoral program in biology in the United States, spent his first year in classes and in his supervisor's laboratory. His supervisor recalled:

> He has been taking the required courses . . . in the beginning he had difficulty with the language and he kept coming back to me saying that he does not know the professional word, which means he didn't know the English word the professor was saying. He could understand the concepts when he read the book, but when the professor was talking he could not understand it, so that made the courses more difficult.

Despite struggles with English, his supervisor reported that Li earned good grades. In the laboratory, Li worked alone on colon cancer research involving mice. Outside the laboratory, however, he regularly met with his supervisor, who recounted:

> We sit down and discuss exactly what the research is. I basically believe in giving an entire picture, and then we break it down into smaller pieces in terms of what can be done this week and the next week and long-term planning.

Despite careful planning, Li described himself as a creative researcher, saying, "I like to do new things and not follow others." Although Li sought to conduct novel research, he reported building on the work of others and using a systematic approach to inquiry. As he described:

> When I first get a new project, I want to read many publications to see the situation in this field and what the others are doing. Then I need to find my topic or task and goals; then I should find some detail to find a way to realize my goals.

Li's supervisor described him as "mature, diligent, and hardworking." However, Li encountered setbacks in his experimental work:

> Because my experiments are with animals I have spent much time with them. If I fail, I have to repeat. [Have you failed much this semester?] Yes, when you do research on colon cancer, you have to make an animal model and it is very hard to get the metastasis in an animal model.

Additionally, Li revealed, "Sometimes I forget to prepare all my things and my supervisor yells at me for this." His supervisor concurred, saying that although Li was very detail oriented, "Sometimes I have to say things twice and draw things out so that we are on the same page." Not surprisingly, Li valued his supervisor's patience, but also her willingness to promote cognitive reflection. Li stated, "My supervisor is a good professor and she has good patience and likes to teach me how to think. Most importantly, she doesn't just direct me; she gives me time to think."

Li's proposal ratings revealed that he entered the program with intermediate to proficient skills in placing his work in context and experimental design, skills he possibly learned in his master's degree program. He scored at the novice level or below on all other subscales. Spring proposal ratings indicated sizable gains in all rubric subscales, raising him to the level of intermediate (with the exception of placing work in context, in which he was already proficient when entering into the program).

### 4.2. Kate's Profile

Kate, a doctoral student in epidemiology, entered her program with a master's degree and several years of experience as a faculty member in public health at a teaching-oriented institution. She spent her first year as a doctoral student immersed in classes ("I'm spending too much time on class work; I need to get back to research") and on the periphery of her faculty supervisor's research team. Three factors placed her at the periphery. First, her skills in manipulating large databases, a prerequisite for research in her area, were weak. Second, her supervisor's two other students had nearly completed their doctorates and were transitioning out of the team, while Kate was his only new doctoral student. Third, funding for her supervisor's work was depleted. Kate reflected:

> Research-wise, it all depends on funding. If the funding doesn't come in, it is all going to fall apart. We're scraping the bottom of the barrel with our funding. He [faculty supervisor] may not even be able to keep me on.

Kate and her supervisor both perceived Kate's need to quickly acquire database management skills to facilitate her full participation in research. However, student peers nearing degree completion and funding concerns appeared to combine, to an extent, to expedite development in Kate's research skills. Kate met with her supervisor two or three times per week to collaborate on papers and grant proposals. Kate recalls: "I've written abstracts; I've written grants; I've written biosketches; I've written methodology; I'm working on two papers, one that will go for submission in June." In addition, Kate was involved in conference presentations. When asked what experiences helped her become a better researcher, she immediately responded, "Conferences—actually seeing people do stuff."

Despite the above, Kate lamented when she compared her current research experience to that of her master's degree:

> With my master's I got to develop my own little thing. Had my own committee, did my whole study design, did everything. I had all the frustrations that go along with research but it wasn't quite like this. Here it is a whole lot different . . . maybe I am just not cut out.

Both Kate and her supervisor agreed about her research weaknesses (analytical skills) and her strengths (linking differing perspectives into a "big picture"). Kate described her working relationship with her faculty supervisor by saying, "I have nothing but respect for the man." Her faculty supervisor described Kate as "energetic and engaging." Kate's research proposal ratings revealed that she entered her doctoral program with a novice skill level across all rubric subscales, with the notable exception of data analysis, in which she was very weak. Spring proposal ratings indicated that Kate scored at the intermediate level with the exception of data selection and conclusions. These exceptions align with interview data indicating that Kate only analyzed pre-existing datasets and focused more on analyses than on drawing conclusions.

### 4.3. Antonio's Profile

As his supervisor recounted, Antonio, a doctoral student in civil engineering, had been "doing research for 14 years" as a university faculty member before he left his native country, Colombia, to attend his doctoral program in the United States. He spent his first year as a doctoral student taking classes and working in his supervisor's laboratory. One class in which he had enrolled was, according to Antonio, "very, very interesting and very motivating to apply to my current research." He described his participation in his supervisor's laboratory by saying:

> I have been involved in several projects from the beginning; I was writing a proposal and have all the results and now we are in conclusions . . . . I have been working on a very important part of getting the problem formulation clear. I think in that part I have been improving because working and formulating the problem are the most important things for the research—to have your problem very clear so you can solve it.

Antonio's supervisor described a positive working relationship with Antonio:

> I think we have a good rhythm. When he [Antonio] has exams and homework and things like that, we meet once a week, but in a normal week, we meet three times a week. It is very smooth actually, the collaboration that we have. We have clear objectives: We have to write this paper, we are going to do this experiment.

Although his supervisor provided Antonio with support, he also provided abundant autonomy:

> I think he [Antonio] has extremely strong research skills. He is the type of person that you can ask, "Hey can we do this?" and he spends days and

> comes back with either more questions because he got stuck somewhere, or saying, "Here is the solution."

Two additional factors emerged to define Antonio's first-year experience as a research assistant. First, Antonio's supervisor held and communicated clear productivity goals for him:

> I hope to write at least four journal papers with him [Antonio] during the time that he is here at the University. . . . That is my goal for his Ph.D., that he gets into that rhythm of writing two or three papers a year. He has also seen how you manage conference papers. Back home, conference papers are not as popular as here in the United States, and also the importance of going to the conferences. You know, just going and meeting people, approaching people and asking about different research. I think it is a complete understanding what our objectives for him here. Me, as a faculty supervisor, what do I expect from him? And he, as a student, what does he expect from me? I think it is a very clear relationship.

Second, although Antonio was only in his first year as a doctoral student, his maturity and experience appeared to affect his laboratory teammates, as his supervisor recalled:

> Something that I have noticed is that after he arrived, my graduate students became more coherent. I have three graduate students, and they do more things together. This was not the case before. I do not know why. I guess he is a good leader in a way. It seems like he says, "We are going to the gym and exercising in the morning and going to work until 6 p.m." or something like that, and you can see all my graduate students kind of doing in the similar pattern. That has actually made my life a little bit easier. I can find them more easily, and they are more interested in what they are doing.

Antonio's research proposal ratings revealed that he entered his doctoral program at the intermediate or proficient level for all skills except those related to reporting results and drawing conclusions. In these areas, his scores were extremely weak. Spring proposal ratings indicated that Antonio made little progress developing skills that were already intermediate or proficient upon entry. Instead, he made substantial progress in reporting results and drawing conclusions.

### 4.4. Lin's Profile

Lin, who earned a master's degree in chemistry in China before beginning her doctoral program in chemistry in the United States, spent her first year in classes, working part time in her department's microscope center, and in her supervisor's laboratory. As a graduate assistant in the microscope center, Lin taught undergraduate and graduate students how to use a variety of microscopes, for example, the electron scanning microscope. Lin recounted, "Personally, I enjoy that position; it is important for the sake of the instruments to have the students be comfortable." Lin also thought this position

increased her mastery of the English language, with which she struggled as she began her doctoral program.

In addition to her work in the microscope center, Lin collaborated with other students to conduct research on fibroblast cells. However, this research was not interdependent. Instead, Lin conducted her own experiments while others in the laboratory conducted theirs. Lin encountered some difficulty in completing her experiments. She recounted:

> I spent the holiday learning how to do the purification of the virus because it is a very complicated protocol. It influences the virus, and you can get different yield. The first time I did that, it was totally wrong because some other user used a bottle as waste and I used it. . . . From this process of the purification, actually I learned a lot, not only depending on somebody to tell you how to do that. Another example is that I used a virus that some other students gave me and they told me what concentration it was and then I used that virus to do the modification. I could not get any product. Then I got confused by the concentration, and finally I failed. The concentration I needed was very diluted, and they gave me a very high concentration. It was very odd. I have learned to not always believe and cannot believe them, and to use your mind to think about that; it is very important. Especially as a scientific student, you have to be aware of that.

Because of her work in the microscope center, Lin interacted with other faculty in her department around research. As a result of these interactions, Lin coauthored a paper with a faculty member who was not her supervisor. She also expressed a commitment to reading primary literature, saying, "Another experience [that contributed to my research skill development] is reading so many papers, because they all relate to your research. Those papers are very important and can give you more ideas." Lin expressed admiration for her faculty supervisor. Her supervisor also shared a positive impression of Lin, stating that she was a member of his research team and he saw her daily. He described her as "hardworking, determined and persistent—she wants to do the research." However, he also did not think that Lin's research skills had changed much in the past academic year, saying, "She needs to work on many things like . . . how to find a real scientific question, and how to start a project."

Lin's research proposal ratings revealed that she entered her doctoral program at or below the novice level at all skills except those related to primary literature, in which she was rated intermediate. Spring proposal ratings indicated that, despite her laboratory work, with the exception of modest growth in validity and reliability and data presentation, Lin made little or no progress developing skills related broadly to methods, results, or discussion. Her sole area of notable gain was in placing her work in context. Thus, Lin's supervisor's estimation that she had made little progress in research skills was, in most skill areas, accurate.

### 4.5. Samir's Profile

Samir entered his doctoral program in biomedical sciences with a bachelor's degree in biotechnology, which he earned in India. Rather than entering his doctoral program with specific research interests, Samir selected his program because of its flexibility. As he shared:

> Biomedical science is a very diverse field and it will give me an introduction to different fields of biology and microbiology, plants and animals, and everything so that I could plan my PhD according to my interests. Once I get an introduction to all these in my degree in biotechnology, then I can now choose where to go, where to put my focus on.

Samir started his doctoral program with about a year of undergraduate research, and he had published two scholarly articles as a result of that work. In his first year of graduate school, he taught two laboratory sections for an introductory biology course. Samir also participated in a required internship program in which he served as a research assistant with a rotating laboratory assignment. Thus, Samir worked in two different research laboratories during the academic year. He found this arrangement beneficial, stating:

> You can explore different laboratories and different types of work and then you decide which ones to choose. I think I have learned a lot during these laboratory assignments, because the assignments that I chose are completely doing different work and different types of techniques.

In both of his laboratory rotation assignments, Samir was part of a research team that included a faculty supervisor and numerous graduate research assistants. When asked about his relationship with his spring rotation faculty supervisor, with whom he had worked for 4 months, Samir reported it to be a positive relationship. As he said, "He is a very nice guy . . . he gives a lot of time to his students, he is never upset, he will never tell you, 'Come on weekends, you have to do the research now.'" Samir's supervisor related:

> Actually I am very happy to advise a graduate student, I do my best to give time for them, to give technical support for them, and if they do not know how to do the experiments, I personally am in the lab to do it for them step-by-step, and watch over it next time they do it by themselves. If they do mistakes, I am patient, I can tell them, "Ok, you don't do it this way; you have to do it this way."

Samir reported his strengths as a researcher were his "passion," "patience," and "troubleshooting." His supervisor reported that Samir was "doing good." His one concern about Samir was that he needed to "read more literature on research that is related to our work." He shared this advice with Samir; however, Samir's supervisor lamented that Samir needed to be reminded of this recommendation more than once.

Samir's research proposal ratings revealed that he entered his doctoral program at the novice level or below for every subscale, with the exception of data selection. Spring proposal ratings indicated that Samir made notable progress in placing his work in context and primary literature. His progress in all other areas, however, was curiously uneven. He made small gains in experimental design and conclusions, but these were more than offset by declines in hypothesis, data selection, and data presentation.

### 4.6. Jin's Profile

Jin, who earned a master's degree in marine science in China before entering a doctoral program in marine biology, found research "very interesting" and "respected by society." During the first year of doctoral study, Jin conducted research in a laboratory with only his faculty supervisor. Both Jin and his supervisor reported a positive relationship. They frequently interacted around research activities and Jin's supervisor also supported Jin as he adapted to local culture. As Jin shared:

> I think we have a really good relationship. My advisor teaches me not only in the knowledge, but also teaches me how to survive in the United States and how to become a scientist in the United States. We work together and talk about beliefs together. So sometimes I think he is a little like my father.

Within their research activities, Jin noted that "the big decisions are decided by the professor, and I will do detailed work." Jin's supervisor echoed this sentiment but described it as a weakness. He observed Jin presenting his research and noted that he failed to explain the big picture of his work. This supervisor shared:

> It is a little bit of concern to me that he jumps into details and basically the audience might even not know what the details are, why are they important, why he is even talking about it. And he kind of gets excited and carried away with those technicalities. . . . He really should work on giving sort of a general perspective of the problem . . . and then move into details.

Jin may have struggled to situate his work in a larger context because, as he perceived, he lacked fundamental knowledge about his area ("My knowledge is not strong enough"). However, his response to this was, "My supervisor is knowledgeable and he can give me the answer." Jin appeared conflicted about this approach, however, because he later relayed:

> You have to figure out something independently. Yeah. The supervisor cannot tell you every detail of things. If he gives you some topic, you should figure it out by yourself, no matter if you use website or ask other students.

In addition, Jin struggled to comprehend primary literature, saying, "My reading skill, when I read a paper, I still feel a little slow to get the idea about that paper." Jin's supervisor was aware that Jin was not regularly reading journal articles, but indicated that by the end of the year, Jin had begun to take his advice:

> For several months I normally would show him some papers, tell him to read or to go through this paper. Now he starts showing me papers, and telling me about what he found in the literature and it's a very good sign.

In contrast, however, Jin did not discuss developing as a researcher through reading. Instead, he anticipated that publishing his research would help him develop his big picture understanding and disciplinary knowledge. As he shared, "I will write, maybe, two papers in this year. So once I write that I will have a better understanding of the whole knowledge related with my subject. I think this will help."

Although Jin's faculty supervisor identified several research deficits, he also noted several of Jin's strengths. Jin's supervisor indicated that Jin "is thoughtful, he works very hard, he concentrates, he has strong quantitative skills." Jin reported his strengths as a researcher included his patience, attention to detail, and logical reasoning. Overall, Jin and his supervisor's research went "smoothly" and they achieved useful results. Jin reported that he "felt so excited" and "proud" because his work contributed to theory and "helped explain some phenomenon about my homeland." Jin's supervisor was pleased with Jin's work and optimistic about his growth as a researcher: "He hasn't been here for a year and yet, he has already produced some paper quality results. It's a really good sign. And . . . [he is] improving, kind of daily."

Jin's research proposal ratings revealed that he entered his doctoral program at the novice level or below for every subscale, with the exception of hypothesis. Spring proposal ratings indicated that Jin made some progress in placing his work in context and good progress in data selection. Like Samir, however, his progress in all other areas was uneven. He made small gains in data presentation and primary literature, but made no gains in data analyses and discussion; he declined in areas related to hypothesis, and reliability and validity.

### 4.7. John's Profile

Prior to graduate school, John imagined himself becoming a dentist, like his brother. However, he did not gain admission to the dental school to which he applied. Thus, after earning a bachelor's degree in biology, he trained to become a hospital laboratory technician, but he did not like the work. Next, John relocated to support his wife's career and allow them to be closer to their family. He then earned admission to a doctoral program in biology to pursue interests in evolutionary biology and genetics.

When John began his doctoral program, he had one year of undergraduate research experience. John described himself as a developing researcher who was "a little bit unsure of [him]self" and "definitely still learning." As a research assistant, he worked on a small laboratory team that included his faculty supervisor and two other research assistants. All worked on projects involving viruses, but the two other research assistants worked on projects different from John's. In addition to his research assistantship, John taught a course in molecular and cell biology, and reported that his teaching often impeded his research progress.

At the start of his doctoral program, John was enthusiastic about research. However, his relationship with his faculty supervisor was uneven. John described his supervisor as "highly intelligent," "someone who's important," but also "somewhat reclusive," someone who "when I go to talk to him . . . he's not mean or anything. . . . He just cuts to whatever it is. Have you ever met someone who never says any greeting?" Despite their trouble in relating, John valued the independence that his faculty supervisor afforded him.

During the course of his first year as a doctoral research assistant, John's relationship with his supervisor deteriorated further. From John's perspective, he felt that his supervisor was unapproachable. As he shared, "I don't want to disturb him too much or to seem ignorant, I guess, so sometimes I don't fully understand but yet I don't want to inquire further." From his supervisor's perspective, John had not followed his advice to seek out ideas from other people and failed to regularly communicate with him. John's supervisor was also frustrated that John had shared one of his research ideas with others without his permission. Overall, he described John as "a drain on me," and "bad for the morale of the laboratory." Thus, John's faculty supervisor ultimately decided to relocate John from the doctoral to the master's degree program.

John's research proposal ratings revealed that he entered his doctoral program with the highest combined fall score total in the participant sample. His fall scores placed him at or near intermediate for the majority of subscales. In all others, he was at or above the novice level. Spring proposal ratings indicated that John made progress only in placing his work in context and data analysis. He evidenced no change or declined on all other spring proposal ratings.

### 4.8. Alex's Profile

Alex held bachelor's and master's degrees in biology and was pursuing his doctorate in biology, all from the same university. He conducted research as an undergraduate, although he described himself as "a terrible student [who] had no care" and "a really low grade point average." Despite this, as Alex shared, his faculty supervisor, "took me in . . . and put me in his master's program and said, 'If you do well your first semester, they won't kick you out.' I did really well . . . and I really appreciate what he's done for me." Thus, when Alex began his doctoral program, he had already worked with his faculty supervisor for 3 years. Both Alex and his supervisor described a positive working relationship. As Alex noted, "We have the type of relationship to where if I'm mad or he upsets me we can yell at each other and we can still be friends afterwards. I can raise my voice if I need to and he'll tell me I'm bad at research and it's all good. I would say we have a great relationship." His supervisor offered a slightly more constrained description of his relationship with Alex, saying, "I think it is good, friendly." When describing himself as a researcher, Alex stated:

> I'm getting better. I know how not to mess up as much as I was in the fall semester. I've learned a lot more techniques and different ways. I am now learning how to understand my results and how to improve them so if I do mess up or I do see a failure, I know how not to do that again.

Despite "messing up," Alex identified several short-term successes in his work. Alex's faculty supervisor helped him connect with other international researchers who were conducting related research and "were very excited" about his work. Thus, Alex was in the process of submitting a research grant proposal that would allow him to further collaborate with these international researchers. Alex was also pleased with the mentorship he had provided to an undergraduate researcher in his laboratory. As Alex noted, "He seems to really enjoy what I'm teaching him. . . . I do quiz him on things . . . just asking him questions and he seems to know everything I ask, so I would say I'm doing pretty good."

Both of these successes involved Alex closely collaborating with others around shared work. During the interview, Alex reflected on the benefits of collaboration, noting that getting feedback on his research from departmental colleagues was his most helpful research experience. As he shared:

> I was doing one part completely totally wrong and kind of got berated in front of all the professors and students. That was probably the best experience. It was somewhat embarrassing, but now I know I can actually finish the project. So that would be one experience, a bad experience turned good.

Alex's fall proposal ratings revealed that he entered his doctoral program with a wide variation in research skill. These ratings indicated pronounced deficiencies in data presentation, conclusions, and limitations, novice skill level in data selection and analysis, intermediate skill level in hypothesis, experimental design, and primary literature, and new proficient skill in placing his work in context. Spring proposal ratings showed no increase for any subscale, many areas of stagnation, and several areas of slight decline.

## 5. Discussion

To what extent does the cognitive apprenticeship model appear to underlie student participants' research development? Walker et al. (2008) write that cognitive apprenticeship is:

> "cognitive" because it makes thought visible through formal representations (talking, writing, mathematical equations and the like), and because it expects teachers and learners to think explicitly about what they're doing (Brown, Collins, & Duguid, 1989; Collins, Brown, & Holum, 1991). It is "apprenticeship" because students move through increasingly complex assignments, getting feedback that leads to improvement. (pp. 109-110)

Study results suggest an abundant display of "cognitive" in terms of making thought visible through formal representations. With the exception of John, supervisor-assistant pairs met regularly, sometimes daily, to discuss research. These meetings were not always described as trouble free. However, descriptions from both supervisors and

assistants indicate in-depth, at times, methodical consideration of ideas and concrete plans for research. Notably, these descriptions occurred more often in profiles of assistants who achieved greater overall skill growth. Anticipating or engaging in collaborative (supervisor-assistant) disciplinary writing was also found in assistant profiles, again more commonly in those who had achieved greater overall skill growth. Disciplinary writing forces explicit reflection of research activities (Yore, Hand, & Florence, 2004) and is, not surprisingly, associated with the development of scientific reasoning skills (Keys, 1995). "Cognitive" also became visible for some assistants through attending conferences (i.e., Kate's experience of "actually seeing people do stuff" at a conference; Antonio's supervisor mentioning the importance of conferences for "approaching people and asking about different research").

Study results are less robust in their display of "apprenticeship" as defined by moving through increasingly complex assignments coupled with feedback. Some profiles lack a sense of purposeful "upward movement" in which the assistant's development was scaffolded by supervisor's feedback as he or she attempted successively more difficult assignments. Instead, apprenticeship appears to be, in some cases, appended to tasks required to complete the experimental study at hand. This is perhaps not surprising, as undoubtedly all supervisors' lines of research had been initiated prior to their assistant joining these efforts. As Kate learned, doctoral research, at least for first-year students, wasn't about "developing my own little thing." Instead, it involved quickly developing and applying the specific research skills required to participate in her supervisor's larger, ongoing project.

Supervisors' feedback on task performance at times appeared to be scarce. For example, Lin's experiences suggest a distinct compartmentalization between her research activities and supervisor feedback. While her supervisor reported seeing Lin daily, their discussions did not, apparently, involve consideration of her laboratory frustrations. Further, Lin's supervisor did not think her research skills had changed much in the previous academic year, and did not seem overly concerned about this stagnation. Alex interpreted his experience of "doing one part [of research] completely totally wrong" and being "berated in front of all the professors and students" as "probably the best experience." However, if his supervisor was providing timely feedback, why was Alex "completely totally wrong" in the first place? Although trial-and-error is possibly an unavoidable part of learning any practice, one is left to consider the waste of human talent and time, especially given the limited duration of doctoral study.

For assistants working as part of a research team, the practice of cognitive apprenticeship may occur between themselves and others beyond the faculty supervisor. Six of the eight assistants reported working as part of a research team, while two (Li and Jin) reported working individually with their faculty supervisor. We were somewhat surprised to find that of the six assistants who participated in a team, only two (Antonio and Alex) seemed at least moderately and positively involved with other team members. Antonio's supervisor (but not Antonio himself) noted the positive effect of Antonio's maturity on others in his laboratory ("after he [Antonio] arrived, my graduate students became more coherent"). Alex interacted closely with an undergraduate researcher ("He [undergraduate

researcher] seems to really enjoy what I'm teaching him"), but not with other graduate students in his laboratory. Of the other four, Kate reported only brief interactions with the two more advanced doctoral students in her supervisor's lab, Lin reported negative experiences ("I have learned to not always believe and cannot believe them"), Samir rotated labs midyear and said little about teammate interactions, and John's supervisor was highly critical because John apparently failed to interact with his teammates. Our sample size is small, and thus our interpretations of the above are offered with caution. We suggest that maintaining a laboratory team is largely dependent on securing external funding, and perhaps some faculty in our supervisor sample were between funding platforms. Alternatively, we note that in a few students' experiences (e.g., John, Lin), students were teammates in name only, and pursued individual inquiry. We can posit with fair certainty, however, that in this assistantship sample, varied supervision was rarely available within teams and little "multiple mentoring" occurred (Copley & Salama, 2010).

Finally, we believe three profiles deserve special attention in the discussion of cognitive apprenticeship and doctoral skill development: specifically, those of Samir, John, and Alex. Each profile represents an aberration from what might be considered the normative doctoral education experience. While rotations are common in some disciplines, such as medicine, they are relatively rare in most of doctoral education (Barker, 1998). Samir's profile represents a chance to consider the relationship between engagement in early-career doctoral rotations and research skill acquisition. Samir valued the rotation format for its ability to introduce him to differing work contexts. However, the opportunity to explore a new context may have come at a cost, as Samir evidenced inconsistent growth in research skill during his first doctoral year. Additional research on the link between rotations and research skill growth is needed, especially within the context of a cognitive apprenticeship model, which would seem to require at least some interpersonal continuity. John's profile is a story of lost opportunities for both John and his supervisor. Clearly their deteriorating relationship suggests concern about placing students under the guidance of a sole supervisor, a concern that is becoming more widely recognized (Copley & Salama, 2010; Walker et al., 2008). Alex's profile represents a conundrum. His narrative is positive, but his proposal ratings suggest that something is missing from his developmental environment, and neither he nor his supervisor seem to be aware of this. Perhaps the lesson is not to rely on a single method to form interpretations about something as important as doctoral skill development.

## 6. Conclusion

When science and engineering doctoral students serve as supervised research assistants, it might be assumed that interactions between supervisors and their students, and between students and other team members, would be particularly potent in the development of research skills, especially when seen through the lens of cognitive apprenticeship. Even within our small sample, our findings suggest otherwise. We do believe cognitive apprenticeship can be and is often the "signature pedagogy" (Golde et al., 2009, p. 54) of doctoral education, but it does not occur by magic; instead, it requires deliberate action by faculty supervisors and students.

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