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Essential Elements of Collaboration: Understanding How Chemistry Graduate Students Experience Collaboration through International Research Visits

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ABSTRACT: This study explores how graduate students learn to participate in collaborative international science research. As part of an NSF-funded program, 21 graduate students participated in extended research visits to China, completing surveys before and after traveling, and participating in semistructured interviews upon returning to the U.S. These survey and interview data were qualitatively analyzed to determine how graduate student participants defined collaboration and how they positioned their own research experience in an international context. Data were coded using emergent thematic analysis via a first pass open-coding to generate a comprehensive list of descriptive codes for collaboration and then a synthesis of these codes through discussions guided by theories of situated learning in communities of practice. Findings suggest that all graduate students emphasized the importance of effective communication in collaboration. Graduate students also described collaboration as including at least one of the following elements: complementary expertise, shared goals, joint publications, and mutual learning. These findings provide insight into graduate students' experiences with collaboration, and, in turn, how to support graduate students so that they have successful international research experiences and collaborations with international colleagues.

KEYWORDS: Graduate Education/Research, Professional Development, Electrochemistry, Curriculum, Collaborative/Cooperative Learning



INTRODUCTION

Scientific practice is increasingly a collaborative endeavor, especially as the world becomes more accessible.¹ As chemistry graduate students prepare for global science practice, they need to develop both an ability to work with people of other cultures and an awareness of the cultural differences for how science is practiced. In graduate school, U.S. students need to learn to work with international students as they represent more than half of science, technology, engineering, and mathematics graduate students.² Once students complete their degree, in both academia and industry, many employers look for “global knowledge” of how to develop working relationships with international colleagues when hiring chemists.³

While the value of international collaborations in chemistry is well-known, then, what remains a challenge is determining how best to help graduate students develop the foundation and skills needed for fostering such professional relationships. One way graduate students can begin to engage in international collaborations is through research experiences abroad. This study examined U.S. graduate students' perspectives on international collaboration after participating in a research

abroad experience in China. From analysis of their perspectives, findings offer key considerations for planning international research visits that build a foundation for collaboration and prepare students for participation in a global science community.

To better understand graduate students' experiences with collaboration, the following research questions were explored:

1. What did graduate students count as a scientific collaboration after they had participated in an extended international research visit?
2. How did participants' definitions of collaboration differ between those who positioned their research visits as successful collaborations and those who positioned their research visits as unsuccessful or partially successful collaborations?

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3. What did graduate students perceive as outcomes for their research visits and in what ways did these relate to collaboration?

LITERATURE BACKGROUND

This section includes an introduction to the conceptual framework of situated learning in communities of practice. Existing studies relating to research abroad experiences and collaborations in science were reviewed, which together provide background for understanding graduate students' perceptions on collaborations in science after participating in research experiences abroad.

Conceptual Framework

Guided by a conceptual framework of situated learning in communities of practice, this study considers learning as situated such that it is a "social phenomenon constituted in the experienced, lived-in world, through legitimate peripheral participation in ongoing social practice" (Lave, 1991, p 64).⁴ In this sense, the context in which learning takes place influences what knowledge and skills are developed by students. Contexts include the specific time, place, activities, materials, and social interactions available, among other considerations. Knowledge is constructed and meaning is negotiated from such situated social interactions.⁵

Additionally, situated learning allows learning to be considered "not as a process of socially shared cognition that results in the end in the internalization of knowledge by individuals, but as a process of becoming a member of a sustained community of practice" (Lave, 1991, p 65).⁴ In the process of becoming a member of a community, knowledge and skills are developed, which in turn shape, motivate, and determine what is valuable within the community. This is especially true of tacit knowledge, such as what research topics are valuable to pursue in chemistry or how to manage a lab, which cannot always be learned explicitly from documents or tools. "Tacit knowledge requires interaction and informal learning processes such as storytelling, conversation, coaching, and apprenticeship of the kind that communities of practice provide" (Wenger et al., 2002, p 13).⁶ In this study, through their participation in an international community of practice, graduate students explored what it means to collaborate and what makes collaborations successful.

Research Abroad Experiences

While much is known about the need and benefits of international research collaborations in science, there is little research on best practices for study abroad experiences for graduate students. Because of these limitations, study abroad research on undergraduates can be used to provide a foundation for how to plan such experiences for graduate students. For instance, Marine's work on study abroad in Europe for Chemistry undergraduates provides detailed suggestions on planning study abroad courses that integrate both scientific and cultural learning.⁷ Best practices from the literature for successful study abroad suggest that students should plan to have an immersive experience in another culture, where they will have encounters with new colleagues and unfamiliar equipment, receive training in a new technique, and contribute to their own research projects.^{8,9} The most crucial difference for graduate students is the independence of the student, especially with regard to planning successful research projects.

In order to benefit from the cultural aspects of international exchange, it is important that students spend more time with members of the host culture rather than among U.S. colleagues. The German Academic Exchange Service Research Internships in Science and Engineering program is one example of an undergraduate research abroad experience centered on research that fosters intercultural relationship-building.¹⁰ In this program, a graduate student hosts an undergraduate scholarship recipient from a different country and works with a hosting group leader to mentor their research, a model that has led to the development of longstanding research networks.¹⁰ Other studies show that maintaining some contact with members of one's own culture, especially early in the study abroad experience, can be beneficial alongside spending time with members of the host culture to help alleviate the loneliness and feelings of alienation that students abroad often encounter.¹¹ In addition, students ideally need opportunities to discuss and reflect upon their experiences in a new culture with someone who understands both cultures,^{12,13} although any discussion and reflection can be helpful for making sense of new experiences.

Graduate students are often reluctant to participate in research abroad experiences. In some ways, their reluctance stems from misconceptions that research abroad is expensive, impractical, or unnecessary since universities in the United States are superior.⁸ Graduate students do not always see the benefit of spending time away from home, fearing that they will not accomplish enough in the foreign lab to make up for their absence. Other graduate students might be unaware of the option of research abroad, how to pursue it, or what the benefits might be.⁹

Most research on how best to design research abroad experiences and the benefits of participating comes from research on undergraduates' experiences. Yet, participating in international experiences can benefit graduate students in many ways, by exposing them to different methods and tools for doing research and different cultural norms, and by broadening their perspectives on science in general.¹⁴ Beyond direct benefits to U.S. students, entrepreneurship is stimulated by cross-border mobility of academics.¹⁵ For example, foreign students studying and collaborating with peers in the U.S. likely increase the number of U.S. patents and publications.¹⁶ Additionally, it has been shown that exposure to another culture makes students more creative, a key aspect of innovation and entrepreneurship, via the following mechanisms: (1) gaining access to unfamiliar concepts and ideas, (2) learning that something familiar can have a different function in a different culture, (3) raising questions or prompting changes in routines, (4) becoming more readily able to integrate information from unfamiliar sources into their existing knowledge base, and (5) seeing connections between ideas from both cultures that might not immediately appear to be related. These benefits are especially likely to occur if exposure to another culture is prolonged and immersive, and if there is some commonality or shared focus that links the two cultures.¹⁷ In theory, an extended research visit could be an ideal scenario for creativity to develop, among other benefits.

Collaborations in Science

International collaborations are increasing in recent years. While research thrives on partnerships among scientists, industry, and more, there have been few studies that look beyond publication counts and, instead, investigate what

Table 1. Study Participants and Comparative Details of Research Abroad

Student Pseudonym	Location in China	Duration of Travel, Days ^a	Research Goal Summaries ^b
Stephen	Suzhou	35	Learn to characterize different types of particles using TEM.
Christopher	Suzhou	32	Learn TEM and gain experience in SEM while acquiring images of materials.
James	Suzhou	20	Gain hands-on TEM experience and SEM.
Christina	Suzhou	20	Learn instrumentation skills for TEM and SEM to acquire quality images.
David	Suzhou	42	Characterize catalyst surfaces using TEM, SEM, hr-TEM, EDX.
Bryce	Dalian	22	Study catalysis on single crystal surfaces under UHV.
Kelly	Beijing	42	Develop alternative approaches to attaching electrochemical mediators to polymer-modified electrodes.
Lei	Dalian	96	Conduct computational studies of heterogeneous catalysts using density functional theory; develop transition state searching algorithms.
Jacob	Suzhou	36	Use TEM/SEM to image Pt loading on carbon nanoparticles.
Max	Xiamen	55	Learn how to make up-converting nanoparticles.
Elise	Shanghai	116	Synthesize and characterize gold nanoparticle–DNA composite materials.
Matthew	Hong Kong	62	Develop synthetic techniques for increasing cancer cell targeting by nanoloaded caged NO photocursors.
Samuel	Fudan	75	Synthesize and characterize multisurface nanoparticle structures.
Amanda	Shanghai	49	Use ligands for uranium chemistry to stabilize new rare earth metal complexes and learn to synthesize new ligands.
Cheung	Beijing	42	Investigate composite dispersion as an electrolytic system.
Kaitlin	Suzhou	25	Learn new characterization techniques and use TEM to characterize transition metal oxide and sulfide nanowires.
Alex	Suzhou	24	Learn how to perform TEM and use TEM to image catalysts (e.g., nanoparticles on the surface of MgO–Al ₂ O ₃).
Kevin	Shanghai	33	Learn from experts in rare earth pnictogen bonding and synthesize scandium and yttrium heteroatom multiple bonds.
Ian	Beijing	31	Work on electro-organic synthesis of chalcone epoxide using composite electrolyte.
John	Beijing	80	Learn more about electro-organic chemistry and work on redox cleavage of lignin model compounds with electrochemistry.
Molly	Shanghai	20	Work with a flow reactor and examine the effect of substrate concentration and amount of catalyst on product distribution.

^aDuration includes the final day of the trip. ^bElectrochemistry techniques include the following: transmission electron microscopy (TEM) where samples can be imaged via a beam of electrons transmitted through the material, scanning electron microscopy (SEM) that produces images by scanning surfaces using electrons, energy dispersive X-ray spectroscopy (EDX) that uses the interaction of an X-ray source and a sample to determine atomic structure and characterize the sample, and ultrahigh vacuums (UHV) that contain low pressures for performing surface science experiments.

constitutes such an alliance.¹⁶ Co-authorship analysis (e.g., Arunachalam and Doss¹⁸) provides insight into which countries collaborate and how the numbers of collaborations have changed over time. Across scientific disciplines, there is an emerging recognition of the need to train doctoral students in skills aside from research, for example, skills such as connecting with foreign colleagues and networks, communicating with the general public, and understanding different cultures.¹⁹ This is especially the case for students and postdoctoral scholars preparing for careers in industry,^{19,20} though these skills have great value in academia as well. Although close proximity collaborations remain the most common,^{18,21} researchers receive more funding for far collaborations.²² Of scientists and engineers in the U.S., 1 in 6 reported working with individuals in other countries.²³ In chemistry, 70% of articles published in the American Chemical Society's journals are from international sources, and 15% of ACS members reside outside of the U.S.²⁴ Graduate students need to be prepared to participate in a collaborative research environment that includes international colleagues.

METHODS

Qualitative methods were used to research graduate students' perceptions of and experiences with scientific collaboration as a result of research visits to China. Graduate students first applied for a fellowship or travel grant with the National Science Foundation (NSF)-funded Partnership for International

Research and Education: Electron Chemistry and Catalysis at Interfaces (PIRE-ECCI) and identified a research group to work with in China. Before leaving, they completed a survey that collected demographic and other baseline data, as well as asked them to describe their research plans and their reasons for participating. While in China, graduate students then conducted research related to electron chemistry and catalysis at interfaces for a period of 3 weeks to several months. After returning, graduate students completed postexperience surveys and interviews. Both surveys and interviews were thematically coded to address the research questions in this study.

Context and Participants

This study was conducted from 2010 to 2015 at a large public research university on the west coast. Participants were graduate research fellows and travel grant recipients from PIRE-ECCI. Each participant spent at least 3 weeks conducting research in China related to electron chemistry and catalysis at interfaces. Though more than 30 graduate students participated in this program over the course of five years, this study uses data from the 21 students who agreed to participate in the research component and who completed the necessary surveys and interviews. A few participants traveled to China for research more than once; however, for consistency, only data collected from their first trip are analyzed here. Table 1 shows the participants, the city of their partner institution in China, the duration of their research, and their overall research goals.

Table 2. Codes, Definitions, and Examples Used To Address the Third Research Question

Code	Definition	Example
Successful	Research experience in China was considered an effective collaboration.	"I took what I learned from experiment and I used another group's knowledge of theory to try and come up with some meaningful results. I think in that sense, it's very collaborative."
Partially successful	Research experience in China was considered only partially effective as a collaboration or led to a future collaboration, but was not one itself.	"Yes and no. I was discouraged because the collaboration was supposed to be a collaboration and it turned out for me being kind of a lackey for them."
Unsuccessful	None of the participants thought their research was unsuccessful as a collaboration.	N/A

Table 3. Themes, Definitions, and Examples Emergent from the Data

Theme	Definition	Example
Communication	Communication was essential for collaborations as part of the process for collaborating and doing research effectively, and as an outcome of collaborating.	"Just keeping an open line of communication, I always thought was the most successful thing about a collaboration. I have had unsuccessful collaborations where it sort of feels like it's a one-way conversation."
Complementary expertise	Collaborations involved people with different proficiencies that supplement each other in skills or perspectives.	"...the merging of you know ah scientific expertise that either party does not have the full range of. Kind of where they meet in the middle."
Shared goals	Collaborations supported and worked toward objectives that were common to both parties.	"Collaborations basically set two people up with the same goal and say let's join forces, we're going to answer this together."
Mutual learning	Collaborations led to a valuable exchange of ideas and learning that helped both parties.	"A successful collaboration, even more than publications, is being able to take something away, like learning something."
Joint publication	Collaborations resulted in coauthored publications.	"I think that for scientific research, publication is the most important result because without publication, you do something, but there is nothing you can prove."

Data Collection Methods

As introduced above, data collection for this study included surveys and interviews. Each graduate student completed a preresearch experience survey prior to traveling and a postresearch experience survey within a month of returning. These surveys were used to determine the duration and research goals for each as well as to triangulate students' interview responses and provide additional details where needed. Graduate students also completed postresearch experience interviews. Seven graduate students were interviewed as two different focus groups of three and four, respectively, who traveled to the same place at the same time. The other 14 interviews were conducted individually, since each traveled to a different university and/or during a different time period.

Interviews were based on a semistructured protocol to initiate informal conversations regarding their experiences in China, their perceptions of collaborations, and how they positioned their own research with regards to collaboration. For instance, participants were asked, "What is an example of a scientific collaboration you have participated in? What do you think made it a collaboration? How would you define scientific collaboration?" These questions helped participants develop a working definition of collaboration. Questions that related their research visits to their definition of collaboration included, "Do you feel your extended visit was a collaboration? If so, in what ways. If not, why not?" Other questions, such as recommendations for travel support and details of their research experiences, were used solely for program evaluation purposes and are not included in this study. Each interview was approximately 1 h in length and was audio recorded and transcribed verbatim.

Data Analysis Methods

Emergent thematic analysis²⁵ was conducted on interview transcripts to determine graduate students' functional definitions of collaboration and the relationship between these definitions and their research experiences abroad. More specifically, to answer the first research question, a first pass

open-coding analysis was conducted to generate a comprehensive list of descriptive codes for collaboration.²⁵ These codes were then synthesized in discussions that were guided by the theory of situated learning in communities of practice.² In these discussions, we assumed that graduate students' perceptions of collaboration were shaped by their participation in a chemistry community abroad by engaging with others who faced similar situations and also further understood upon coming home and reflecting on their new experiences. Using this framework of situated learning in communities of practice, we were able to carefully examine statements that compared ideas about collaboration at the boundaries of social learning systems, such as how graduate students' experiences working with others abroad aligned with their individual ideals about collaboration and examples from working in social systems at home.⁶ Data were then recoded by each author using the condensed codes and their definitions. Coding was an iterative process, in which the authors adjusted codes and refined operational definitions until 100% inter-rater agreement was achieved. The authors looked for emergent themes across coded data and selected representative examples for each theme.

To answer the second research question, three a priori codes related to perceived success of collaborations in China were used: successful, partially successful, and not successful. These codes were applied to each student's research visits based on their responses. Table 2 shows the codes for perceived collaboration success along with their definitions and examples.

To answer the third research question, a combination of survey and interview data where students described outcomes from their research abroad were used. Coding for experienced outcomes was emergent and organic. Because students were not asked for an exhaustive list, these methods are simply an exploratory analysis of the types of outcomes that graduate students may experience from participating in research abroad.

FINDINGS

Five themes emerged from coding as key elements of graduate students' definitions for collaborations: complementary expertise, shared goals, joint publications, mutual learning, and, pervasive across all of these, communication. Themes, definitions, and examples of each theme are included in Table 3.

The most common of these themes, in addition to communication, was the idea that a collaboration should be among individuals who possessed complementary knowledge and skill sets. Shared goals with collaborators was also considered important by many graduate students, who expressed that willingness and motivation to work toward the same outcome was a critical element. For some students, simply learning from one another was sufficient to define their interactions with another research team as a successful collaboration. Other students felt that more concrete outcomes, in particular joint publications, were a factor in determining whether or not their work with others was considered a collaboration. Figure 1 shows the percentage of students

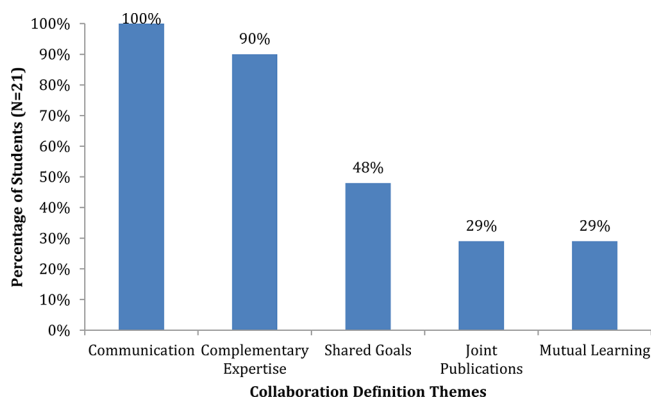


Figure 1. Collaboration themes in students' definitions after participating in research abroad.

reporting each of these themes as they defined collaboration. Finally, effective communication appeared as a component in each of the previous four themes. Communication was featured prominently as both a necessary condition and outcome of successful collaborations. Each of these findings is discussed in more detail in the sections that follow to answer research question 1: What did graduate students count as a scientific collaboration after they had participated in an extended international research visit?

Following a discussion of the five themes, these were compared to students' perspectives of their research visit's success to answer research question 2: How did participants' definitions of collaboration differ between those who positioned their research visits as successful collaborations and those who positioned their research visits as unsuccessful or partially successful collaborations? Figure 2 shows the percentage of students reporting each theme for collaboration divided by whether they felt their research visit was successful or only partially successful.

Last, an exploratory analysis of the outcomes students experienced from their research visits is presented to address research question 3: What did graduate students perceive as outcomes for their research visits and in what ways did these relate to collaboration? These findings provide insight into the

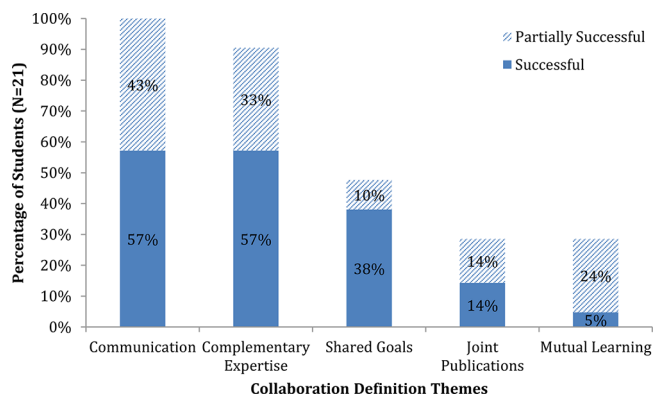


Figure 2. Collaboration themes in students' definitions after participating in research abroad by whether they positioned their experience as a successful or partially successful collaboration.

potential value of research experiences abroad for graduate students.

Components of Collaboration

Complementary Expertise. Most graduate students interviewed (90%) included *complementary expertise* in their definitions of collaboration. These students strongly valued collaborations with researchers who had different expertise from their own and thought that collaborations needed people with skills that complemented each other in a meaningful way. For example, a graduate student with expertise in making materials worked with colleagues in China who had expertise in characterization techniques. When asked how she would define scientific collaboration, Kaitlin explained that collaboration is "just that, the merging of scientific expertise that either party does not have the full range of. Kind of where they meet in the middle." Samuel also noted that collaboration could include the process of building relationships with people who had complementary expertise to one's own. For him, collaboration was a process of networking with people who had different skills.

Having complementary expertise to that of their hosts helped graduate students feel like their skills were valued. In the case of Kelly, her collaborators in China had expertise with mediators while her expertise was modification of the electrode; there were equal contributions toward making it work, and everyone wanted to help, which made the collaboration successful. In short, for most graduate student participants, collaboration is defined by a working relationship between people who have complementary expertise.

Shared Goals. Nearly half of the graduate student participants interviewed (48%) included *shared goals* as part of their definitions of collaboration. Indeed, all participants whose definition contained shared goals also included complementary expertise. These graduate students thought that collaborations should include researchers with complementary expertise who come together to work toward common goals. Graduate students explained the importance of collaborators who were willing and motivated to work toward the goal. As John described the collaborative nature of his research abroad experience, "I think the reason why it is a collaboration is because we talked about our projects, like what we want to accomplish. We were on the same goal." This was true for Elise as well, who described complementary expertise in the context of working toward a shared goal. As she explained, "The key element of a collaboration is when people

with different expertise, different backgrounds come together to work on a common project, a common goal where both of their expertise and the ones that aren't mutually shared are really key to solving the problem and getting something done." In this sense, to repeat, almost half of the graduate student participants thought that collaboration is research-goal oriented and that achieving such goals requires complementary expertise.

Joint Publications. Joint publication, a third theme, was considered a requirement of collaborations for 29% of graduate student participants. Ian (who published a joint paper) explained of the general importance for publications, "I think that for scientific research, publication is the most important result because without the publication you do something, but there is nothing you can prove." For Ian, this act of proving his research worked was only evident through publishing. Other students were of a different opinion. As Lei (who also published a joint paper) asserted, "I don't think that the publication needs to be there. At least from my point of view of being a doctoral student, I mean we're still students so learning takes priority. I know there's been a lot of emphasis on publications, but just because if the experiment and the theory don't match that tells you something and that can help you in future work in solving problems. So, it's never a waste." For Lei, the most important part of collaboration as a graduate student was learning, regardless of whether that learning results in a joint publication.

Mutual Learning. Another goal that 29% of students also identified as part of scientific collaboration is mutual learning. In some ways, these students thought of mutual learning as the minimum requirement for a collaboration. In this sense, even if no findings or publications resulted, students still defined collaboration by having mutual learning as a valuable outcome. Graduate students thought that collaborations need a balance in learning so that both parties benefit. As Max explained, "Collaboration, even more than publications, is being able to take something away—like learning something. In my case, I'd call it a successful collaboration only because I was able to learn a lot more than I would have by doing this work on my own." With regards to what learning takes place, students seemed to differ. For some, the learning needed to be technical and directly relate to research. For others, learning could still be balanced even if the collaborators learned different skills entirely. As Elise explained of her own mutual learning experiences, "I think collaboration is mutual although I do think that there's a lot that goes on other than learning technical skills. For example, in China something that's actually resulted in a publication already is that I helped a lot of the students write in English and in that way it was a collaboration." In this case, the shared knowledge was language and teaching skills rather than a solely technical exchange.

Communication. Pervasive across each of the collaboration themes discussed above was communication. Regardless of other aspects of their definitions, all students thought that effective communication was of paramount importance for a collaboration. As Samuel described, "Just keeping an open line of communication, I always thought was the most successful thing about a collaboration. I have had unsuccessful collaborations where it sort of feels like it's a one-way conversation." Students felt that communication was easier with closer proximity, which made traveling essential for international collaboration. Frequency of communication also played a role, though it was mostly emphasized in terms of problems that arose when the frequency of communication was insufficient for moving research forward. Communication was

also discussed in terms of quality, especially with graduate students reflecting on their own outcomes, learning to communicate their research better as a result of their experiences abroad. In fact, communication was perceived as both a necessity for collaboration and an outcome.

Students positioned their ideas about communication with their definitions for collaboration. For example, Kevin aligned communication with his ideas of collaboration as *complementary expertise* and *shared goals* when he said, "Everyone needs to just kind of be on the ball with their specific expertise area of the collaboration... you definitely need people who are on the ball with their part and if they are having difficulties, just back and forth open communication about the whole project and whatever your goals are would be essential." When Amanda, who had a similar definition, responded to the question regarding what made your research visit a collaboration, she emphasized, "Communication. We knew exactly what they were trying to do and vice versa. We had a skill set that they didn't have." For students like Kevin and Amanda, applying *complementary expertise* and *sharing goals* was impossible without each party being able and willing to communicate.

Communication was also critical for John, whose definition of collaboration focused more on *joint publication*. As he explained, "Communication, like the share of experience, the share of your knowledge. This is the most important part. I mean if you just go somewhere with better equipment, of course you can work but it doesn't mean you'll have some breakthrough in your mindset. I think that is the most important thing about science is you get something done and you can tell people what you've done." For him, communication came after the research, in the act of sharing results, yet it was required for collaborations to be successful.

Students mentioned communication as not only part of their process for collaborating and doing research effectively, but also as an outcome (as discussed further in the third findings section on outcomes below). They thought that having to communicate their ideas to colleagues with different research strengths, cultural backgrounds, and languages helped make them better communicators and better chemists.

Research Abroad Experiences as Successful Collaborations

Over half of the students in this study (57%) thought that their research visit to China was a successful collaboration and all of these defined collaboration as having aspects of *communication*. The remaining 9 students reported that their visits were only partially successful as collaborations, meaning that their experiences did not meet their full criteria for a successful collaboration. Of the 48% of students who included *shared goals* in their definition of collaboration, a greater percentage positioned their research experiences as successful rather than partially successful. For the 90% of students who included *complementary expertise*, almost 2/3 positioned their research as successful. For example, a graduate student who defined collaboration as having shared goals and complementary expertise perceived their experiences as successful because she had expertise in making and analyzing the surface structure of catalytic materials and she collaborated with experts in China who specialized in electron microscopy imaging. Their shared goal was to characterize catalyst surfaces of materials using TEM and SEM, and together, they successfully obtained and analyzed images of materials the graduate student had made that helped her better understand the catalyst surfaces of these materials and make new materials.

Considering joint publications as an important part of collaboration did not seem to connect to whether or not a student actually published as a result of their research experience in China. At the time of their interviews, most students were unsure whether a publication would result from their research experience. Even so, for some students, this outcome was a deciding factor for the success of their collaboration. For the 28% of students who included *joint publications*, an equal number considered their research experience successful and partially successful.

On the other hand, of the 29% of students who included *mutual learning* in their definitions of collaboration, more (24%) positioned their experiences as only partially successful. In short, students who viewed collaboration as people who have shared goals were more likely to consider their collaboration as successful when compared to those who felt collaboration was defined by mutual learning (which in some cases resulted in more one-sided outcomes). Figure 2 shows the percentage of students with each definition theme who perceived their experience as a successful or partially successful collaboration.

Research Abroad Experience Outcomes

Some students provided descriptions of the outcomes they experienced as a result of their research visits. Since the topic of outcomes emerged organically in some interviews and not others, and since participants were not directly asked to provide the researchers with a complete list of experienced or expected outcomes, the descriptions of outcomes provided in this paper cannot be considered an exhaustive list. However, the examples graduate student participants provided give valuable insight into the potential benefits of research visits abroad and what outcomes were likely the result of successful collaborations.

Outcomes generally fell into one of three interrelated categories: interpersonal skills, expanded professional networks, and professional and scientific achievements. Graduate students often noticed improvements in their interpersonal skills, such as how to participate in one-on-one discussions about their science research and adapt presentations for groups from different science disciplines. Furthermore, immersion in a different cultural environment provided opportunities for the students to develop cultural insights and awareness. These insights were sometimes based on their observations of Chinese culture in general, but students also reflected on the ways that cultural differences influenced the practice of science. Overcoming the challenges of the research experience, both personal and intellectual, imbued some students with a greater sense of confidence, and a feeling that they had become more independent as scientists.

Working alongside new people in a new environment naturally fostered new professional relationships for graduate students, which they often considered a substantial benefit of the research abroad experience. While some participants mentioned all of the new contacts they had established abroad, others went further and described collaborations that they were currently engaged in or hoped to become engaged in as a result of their time in China. Becoming a member of a wider network of scientists provided more opportunities for collaboration, as both U.S. and Chinese participants became more aware of who potential collaborators might be. Those who successfully initiated or continued collaborations that emerged from their research abroad experiences served as examples to other graduate students that such an outcome was not only possible, but desirable.

Students often described achievements based on what they learned. Experiences with new people and new equipment provided opportunities for participants to learn research skills, whether that was a new way of thinking about their problem, new knowledge, or new mastery of unfamiliar instruments or techniques. For a few participants, the skills and knowledge developed during their research abroad experiences resulted in a decision to change their research or career directions. In many cases, new skills and knowledge resulted in a publication for a participant, coauthored by American and Chinese scholars. As of 2015, 8 of the 21 participants in this study had published a paper from their research abroad experience. In total, this group of 8 graduate students had 11 publications. The skills and knowledge gained by graduate students were the direct result of mentoring and collaborations with their Chinese hosts. Tangible outcomes like publications were the clear fruits of such collaborative work.

DISCUSSION

Findings in this study illustrate graduate students' perspectives on scientific collaboration after participating in a research experience in China. Participants were interviewed and surveyed following their experiences to determine how they defined collaboration and how they positioned their own research experience. These graduate students described collaboration as including at least two of the following five elements: complementary expertise, shared goals, joint publications, mutual learning, and communication. After communication, complementary expertise was the most common theme graduate students included in their definitions of collaboration. Pervasive across other themes was the importance of effective communication. Communication was considered a necessary ingredient of collaborations as well as an outcome. Furthermore, collaborations were most successful for students who included complementary expertise or shared goals in their definition. On the other hand, students who prioritized mutual learning or joint publications more frequently described their collaborations as only partially successful. This could be due to a focus on outcomes rather than the process itself, making it difficult for collaborations to be successful if the outcomes are only partially accomplished. Further research could investigate distinctions between outcome-based and process-based perceptions. Regardless of whether graduate students considered collaborations to be successful or only partially successful, they reported a myriad of outcomes including interpersonal skills, expanded professional networks, and professional and scientific achievements. This study highlights the need for research that understands how students enter international communities of practice and, in doing this, the need to learn what makes collaborations successful and how to collaborate successfully. As graduate students participate in a community of chemists, whether in their home country or abroad, they develop tacit knowledge of what it means to collaborate. From the framework of situated learning, such tacit knowledge is then shared with others (both abroad and at home) to shape and determine what is valuable in a community. This research serves to make tacit knowledge more explicit with implications for preparing graduate students to participate in a global science community of practice. Using a framework of situated learning in communities of practice, we were able to understand students' research experiences abroad, and, through comparison and reflection, how these experiences then shaped their ideas about collaboration more broadly. This

understanding can help novice chemists learn explicit ways to collaborate so that they can better enter and participate in a global community of practice.

Findings about graduate students' perceptions of international collaboration in chemistry suggest that programs provide opportunities for graduate students to effectively communicate with people who have complementary expertise on projects that focus on a common goal. Such efforts could result in both parties learning and publishing together, though the efforts will likely be most successful if they focus on supporting the collaborative process. Communication is essential as both an aspect of the collaboration and as an outcome in itself. Communication between those of different research and cultural backgrounds provides opportunities for students to adapt the ways they discuss their own research toward a new audience and develop strategies for sharing ideas. Not all students will have the opportunity to participate in research abroad, but it is from the perspective of students with this experience that chemistry can create opportunities to learn elements of such collaborations. For teaching, findings suggest that faculty structure teamwork in laboratories and projects so that students have to first identify common goals and the strengths of their collaborators. In addition, this research can provide insight into mindsets that help graduate students become and feel more successful working with international colleagues. For example, focusing on growth of communication skills and relationship-building can help graduate students succeed in working with others in their home country as well as have successful and productive research experiences abroad.

While understanding graduate students' perspectives on international scientific collaboration has implications for teaching students to collaborate effectively and helping them have successful research abroad experiences, this study has some limitations. The study population consists of U.S. graduate students who conducted research in China and is thus limited by geographic and ethnic scope. Students in other countries or those working with colleagues of different nationalities may perceive collaboration differently and need different support in developing such relationships. Additionally, this study is limited by the number of participants researched. While this research sought to understand collaboration in a rich qualitative context, gaining a deep perspective limited the ability to understand a broader portion of the population. Despite limitations, this in-depth study of international collaboration can provide further opportunities for preparing graduate students to participate in global science research as well as a foundation for further research efforts supporting such preparation.

To better understand international chemistry collaborations, additional research would be valuable. Such studies could expand the geographic scope, increase the number of participants, and/or include more diverse participants which may yield additional perspectives applicable to a broader population. Additionally, longitudinal tracking is beneficial for understanding outcomes that may occur beyond the scope of the study. Specifically for this study, longitudinal tracking would help better understand the connections between graduate students' perspectives of collaboration and the longevity and productivity of their collaborations. It is important to connect these concepts in order to foster outcomes from international research experiences and prepare graduate students for developing international research collaborations.

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