

The Development of Expertise in Scientific Research

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Abstract

Scientific research is a fundamental mechanism for both advancing human knowledge about the natural world and facilitating technological innovations that fuel economic development. As such, understanding and optimizing the pathways to expertise and professional success in this endeavor is vital to ensure sustained intellectual and financial benefits of scientific research. This essay summarizes the research on the development of expertise in the sciences from the psychology of science and research on graduate education. Examining new research trends that present an emerging picture of a specific trajectory for the development of research skills and frame the development of scientific research skills as direct outcomes of specific training practices, new directions for research that bridge the cognitive and socialization lenses are identified.

INTRODUCTION

Scientific research is a fundamental mechanism for both advancing human knowledge about the natural world and facilitating technological innovations that fuel economic development. As such, understanding and optimizing the pathways to expertise and professional success in this endeavor is vital to ensure sustained intellectual and financial benefits of scientific research. As a general practice, science uses empirical evidence and logical inference to identify generalizable principles that explain the mechanisms of natural phenomena. It also reflects standards of quality judged by replicability (i.e., empirical findings supporting a conclusion can be obtained consistently across studies) and parsimony (i.e., the ability of an empirically supported theory to explain the widest possible range of instances in the simplest way). Although the nature of scientific work has changed dramatically in recent decades with regard to pace, structure of research teams, relevant technologies, and sources of funding (Austin & McDaniels, 2006), the core facets of expertise in conducting scientific

research have remained stable: Scientists must systematically collect, analyze, and interpret data about the natural world and effectively present their conclusions in a manner that meets the standards of rigor, relevance, and novelty.

Expertise in scientific research requires more nuanced consideration, however. The science disciplines (e.g., biology and chemistry) can be understood as distinct intellectual endeavors within which scholars share common sets of research questions, methods of inquiry, and intellectual approaches to solving problems (Kuhn, 1962). Disciplines manifest their differences from one another through distinctions in the use and value of different forms of evidence (e.g., logical, observational, or experimental) or the privileging of data-driven (inductive) or theory-driven (deductive) modes of reasoning (Bauer, 1992). Thus, each discipline maintains its own “epistemic culture” (Knorr-Cetina, 1997, p. 260) with its own norms, jargon, theories, and essential skills that can overlap to varying degrees with another. Accordingly, expertise is most precisely characterized within a disciplinary context, and even categories of skills frequently conceptualized across the sciences make reference to the state or standards of the discipline. For example, research skills that are commonly measured across disciplines include identifying and framing a meaningful and productive question for investigation based on the existing state of knowledge in the researcher’s discipline, formulating a testable research hypothesis based on a specific question, designing a valid experiment or empirical test of the hypothesis, and interpreting data by relating results to the original hypothesis and drawing appropriate, supportable conclusions (Kardash, 2000). Collectively, these skills result in the construction of disciplinary arguments within a scientific discipline, the mastery of which is considered essential for successful scientists (Kiley & Wisker, 2009).

Beyond the component skills required to produce valid and accepted research, scientists also become recognized as experts for the importance of their research findings in terms of the impact that they have on the accepted understanding or practical application of the phenomena of interest. Increasingly, interdisciplinary research is proving effective for understanding many complex problems, despite the significant challenges it poses for scientists to communicate and collaborate across disciplinary lines (Lattuca, 2001). However, its practice arises from the border traffic between disciplines, which serve as the foundations for complementary modes of expertise (Frodeman & Mitcham, 2007). As such, the discrete disciplinary foundations of scientific expertise collectively frame a larger problem, which is essential for productive interdisciplinary research.

FOUNDATIONAL RESEARCH

Two traditions frame the current understanding of expertise development in research. The first is the psychology of science, which characterizes the cognitive mechanisms of scientific reasoning. The second is socialization theory, which frames the development of research competence as a transactional process of learning to participate as a member of a specific disciplinary community—often under a mentor’s guidance in the form of a cognitive apprenticeship.

COGNITION IN SCIENTIFIC PROBLEM SOLVING

In the cognitive tradition, solving problems for which solutions are not yet known is often referred to as the search of a problem space. The space is composed of all possible routes to move from the initial state of knowledge (i.e., all relevant known and unknown factors) to the solution (Newell & Simon, 1972). Experts navigate smaller problem spaces than novices because the number of possible routes is constrained by the knowledge of the individual attempting to solve the problem. Strategies known to be ineffective or inapplicable within the constraints of the problem or disciplinary lens are excluded from the solution search preemptively.

Klahr and Dunbar (1988) conceptualize scientific problem solving as the simultaneous search of two adjacent, interacting problem spaces: the *theoretical* space (What is the correct explanation or principle?) and the *methodological* space (What are the effective means of investigating its validity?). To resolve the theoretical problem, scientists select a hypothesis based on a synthesis of current knowledge in the field that yields the most likely explanation or appropriate governing principle. Selection of this conjecture constrains the possible range of research designs because it specifies what type of events must be observed and what measures should be used to align with the theoretical framework identified. Similarly, selection of a research methodology constrains the possible findings and derivative conclusions because choices have been made about which aspects of the phenomenon will and will not be examined. Thus, what is known about a problem constrains the range of possible solution paths through the problem space, which possible solution paths are attempted determine the data obtained, and those data in turn inform the conclusions reached. As each conclusion shapes the theoretical understanding of the problem, the knowledge-based constraints on the search of the methodological problem space change, resulting in new experimental designs that can in turn yield novel insights to advance the theories used to explain the phenomenon.

Given the large number of possible paths in the search of each problem space and the many reciprocal interactions that can change the problem space

constraints, an essential component of research training is developing the ability to define research problems as narrowly as possible to establish a problem space of manageable size within which to work (Klahr & Simon, 2001). One trait of expert scientists working in their own domains of expertise is the use of optimized strategies in the design of new research. When asked to design experiments to solve problems out of their field of specialization, the efficiency of their problem-solving strategies decreases (Schraagen, 1993).

Scientists also use a number of well-documented cognitive strategies to aid in their navigation of the theoretical and methodological problem spaces. For example, expert scientists make extensive use of analogical reasoning to focus on solution paths that have increased likelihoods of success. Across many studies, experts' verbalized thinking includes a consistent pattern of finding similarities between new problems and those that have been previously solved (Nersessian & Chandrasekharan, 2009). A second key practice is mental simulation, in which scientists conceptualize likely outcomes by mentally constructing new scenarios within their mental models of relevant theory and projecting how known mechanisms will operate under new conditions (Christensen & Schunn, 2009). In addition, across both conceptual and physical experimentation, experts utilize external representations of observed phenomena and their thinking about them to manage mental load such as diagrams, specialized notation systems, and standardized computational algorithms (Cheng & Simon, 1995).

SOCIALIZATION AND COGNITIVE APPRENTICESHIP AS MECHANISMS OF EXPERTISE DEVELOPMENT

The training of scientists overwhelmingly takes place in university graduate programs. Attainment of the PhD is intended to signal the readiness of a scientist to contribute to their chosen discipline through the independent production of research (Lovitts, 2001). The process of graduate education is often conceptualized as a process of acculturating a student into their chosen discipline (Austin & McDaniels, 2006). Models of graduate student socialization entail both formal and informal interactions with both formal mentors and "significant others ... in a department, a laboratory, a disciplinary network, or a university and its resources" (Pearson & Brew, 2002, p. 141).

Among these varied influences, the faculty mentor is generally held to be primary with the responsibility for structuring a student's cognitive apprenticeship. As a concept, cognitive apprenticeship was originally developed as an instructional paradigm for informal secondary school settings. However, it is now a fixture in graduate education to the extent that it is considered "the signature pedagogy of doctoral education" (Golde, Conklin Bueschel, Jones, & Walker, 2009, p. 54).

Cognitive apprenticeships are intended to be a structured way to make visible the problem-solving processes of the scientist through modeling, scaffolding, and coaching in order to nurture the mentee's development of expertise. This process is especially important for the sciences because much of the work performed is conceptual in nature and thus not directly observable. Indeed, Delamont and Atkinson (2001) suggest that successful students "master ... tacit, indeterminate skills and knowledge, produce usable results, and become professional scientists [who] learn to write public accounts of their investigations which omit the uncertainties, contingencies, and personal craft skills" (p. 88). Consequently, graduate student engagement in supervised research activity is linked both to students' perceptions of their own research abilities and their identities as scientists (Holley, 2009). To account for the broader group of individuals who interact around disciplinary topics and the process of research, distributed mentorship can occur through a "community of practice" in which "the participants actively communicate about and engage in the skills involved in expertise, where expertise is understood as the practice of solving problems and carrying out tasks in a domain" (Collins, Brown, & Holum, 1991, p. 16). Specific to the context of research training that typically takes place within research laboratory settings, the community of practice takes on the form of "cascade mentoring" in a research lab setting, in which "postdoctoral fellows mentor senior graduate students, senior graduate students mentor junior graduate students, and junior graduate students mentor undergraduates" (Golde *et al.*, 2009, p. 57).

Cascade mentoring likely plays a critical role in the preparation of future scientists because the traditional faculty mentor role is "marked by neglect, abandonment, and indifference" (Johnson, Lee, & Green, 2000, p. 136) due to research incentive mechanisms that value research productivity over instructional responsibilities (Anderson *et al.*, 2011). A supportive community of practice is particularly critical at the initial stages of graduate work, as many novice students do not fully understand the most effective ways to navigate their training opportunities or the expectations held for their work (Golde & Dore, 2001). However, expressions of concern about poor or erratic graduate research mentorship throughout the doctoral process are prevalent (Lovitts, 2001), to the extent that some researchers in the field suggest it may be unavoidable (Johnson *et al.*, 2000). While students consistently gain exposure to and practice conducting research-relevant tasks, evidence suggests that faculty do not necessarily change the level of challenge or nature of the work assigned to their mentees in response to their progressive skill development (Maher, Gilmore, Feldon, & Davis, 2013).

CUTTING-EDGE RESEARCH

Graduate research training is intended to provide students with the necessary experiences and guidance to develop from a consumer into a producer of research (Weidman, 2010). This process involves a clear sense of skill development, that is, of learning the skills necessary for experts in the field. However, there is surprisingly little research assessing the effects of specific training practices on the extent or efficiency with which targeted skills are acquired. Consequently, current research on the training of scientists has shifted the focus of inquiry from descriptive studies to deeper understanding of the developmental pathways traveled by students as they progress toward the status of independent researchers. There are also an increasing number of studies that evaluate the impacts of specific training components in controlled studies. This work is exciting because it helps to develop a more mechanistic understanding of the training process to the point that it could inform training decisions made by faculty and the structuring of graduate programs.

TRAJECTORIES IN THE DEVELOPMENT OF RESEARCH SKILLS

One approach to the conceptualization of skill development is that of *threshold concepts*, which identifies knowledge and skills that act as bottlenecks to further expertise development. These concepts are inherently challenging to understand, and once attained, entail a fundamental restructuring of knowledge that must precede deeper comprehension of advanced disciplinary perspectives. Through interviews with experienced faculty mentors, Kiley and Wisker (2009) identify three potential threshold concepts: the need to create knowledge, the need for rigorous analysis (i.e., objectivity in the evaluation of argument), and a developed sense of paradigm. Attainment of these skills is considered to be neither gradual nor linear and requires mastery of certain knowledge or skills before the attainment of others. This implies that thresholds are part of a developmental sequence and that they fundamentally alter students' abilities to master other subsequent concepts.

The new contribution of these ideas, which otherwise align well with conventional wisdom regarding the nature of independent scholarship, is the assumption that these thresholds are crossed in a developmental sequence and that they fundamentally alter students' abilities to master other, subsequent concepts. If empirical data reflect a series of thresholds that are intrinsic to research skill development, then doctoral programs could increase their efficiency and effectiveness by sequencing educational experiences to target the attainment of threshold concepts upon which others are contingent.

Timmerman, Feldon, Maher, Strickland, and Gilmore (2013) provide converging and support for these thresholds at a more nuanced level using a

sample of graduate students from across science disciplines. If research skills develop sequentially, then scores on the performance of some skills should be systematically higher than scores on the performance of others at a given point in time. However, if all skills develop in parallel or the sequencing of skill development is arbitrary, predictive relationships among skills would not be evident. In a quantitative analysis of graduate students' performance on written research proposals, students' demonstration of some skills were contingent upon higher scores in others. That is, basic proficiency on certain key skills was not demonstrated unless higher levels of performance were evident in other areas. Specifically, strong performance in the use of primary literature predicted students' ability to situate their work within their respective disciplines and their ability to appropriately frame research problems (i.e., establish testable hypotheses) predicted lower levels of performance on other skills (e.g., data analysis and drawing conclusions based on data), suggesting that proficiency in the former are necessary precursors to the development of the latter.

These trajectories in skill development do not seem to vary based on the point in students' education where they begin research training. Gilmore, Veyra, Timmerman, Feldon, and Maher (2015) found that first-year graduate students who had participated in research experiences as undergraduates demonstrated higher levels of research skills at the beginning of their graduate studies than peers without those experiences. After one academic year, several of the initial advantages remained statistically significant. Further, performance gaps between students further along the skill development trajectory and those with lower levels of proficiency tend to widen over time, indicating an acceleration of competency development with increased opportunities to engage in supervised research (Feldon, Maher, Peugh, & Roksa, 2016).

EVALUATION OF SPECIFIC RESEARCH TRAINING PRACTICES

Research skill development is not a purely cognitive phenomenon. It also entails interaction with the environment—the research laboratory, the academic program, and the larger discipline—as well as specific behaviors, such as mentored research activities, writing for publication (faculty–student coauthoring), and graduate student teaching. The importance of these aspects of socialization for persistence in doctoral programs is well documented (Lovitts, 2001), but direct impacts and interactions among these activities for skill development have not been thoroughly researched. Most scientists receive little or no training in instructional practices (Bianchini, Whitney, Breton, & Hilton-Brown, 2001) and rely on recollections of their own graduate school experiences to inform their decisions on how best to train the students under their supervision. Therefore, new research on the

effectiveness of specific practices is especially important for improving the quality of research training.

Studies of the impacts of mentorship traditionally examine levels of scholarly productivity as the primary outcome. Paglis, Green, and Bauer (2006) found that mentored research experiences, coupled with faculty–student coauthoring, in the second year of a PhD program positively predicted the quantity of published research 4 years later. Similar results have been obtained in other studies (e.g., Kademani, Kalyane, Kumar, & Mohan, 2005). However, publications are not inherently a valid measure of scientific expertise in the sense of individual skills because work is typically distributed over multiple authors who may make greater or lesser contributions to various aspects of the project (Feldon, Maher, & Timmerman, 2010).

While not an examination of skill outcomes per se, one recent study compared graduate students' assessments of their own research skills with their mentors' assessments (Feldon, Maher, Hurst, & Timmerman, 2015). It also compared the students' and mentors' perspectives with performance-based assessments conducted by blind raters in the students' respective disciplines as a way to understand mentors' ability to accurately gauge student skill development. The findings reflected very poor alignment across the three sources of assessment. Specifically, students and their faculty mentors disagreed about whether specific research skills were strengths or weaknesses of the students in 44% of cases. Further, neither the students nor their mentors were able to predict blind-rated performance at better than chance levels. This raises important concerns about the assumption that faculty mentors hold privileged insights into students' skill development because mentors' opinions of students' research skills are frequently utilized to both inform instructional within the context of the student's graduate training, as well as decisions about the structure of an academic program. Further, such evaluations serve as the foundation for subsequent letters of recommendation and the provision of additional opportunities for students perceived to be highly skilled (Green & Bauer, 1995).

Research on the importance of coauthoring with faculty as a graduate training experience for future scientists has become prevalent in recent years. The specific pedagogical practices employed by faculty when writing with graduate students have been documented and framed within a context of socialization to the relevant academic discipline in response to calls for more deliberate approaches to coauthorship as a training vehicle (Kamler, 2008). Qualitative research across multiple countries has provided evidence supporting its importance for skill development. However, only one study to date has directly compared the skill development of students coauthored with faculty mentors with those who did not. It found that faculty–student coauthorship uniquely accounted for 7% of the variance in skill development

over the course of an academic year, representing a moderate positive effect of coauthorship (Feldon, Shukla, & Maher, 2016).

Graduate students in the sciences are often assigned teaching responsibilities at the undergraduate level. However, the culture at many research universities holds that teaching interferes with the development of research skill by limiting the time a student can spend working in the laboratory (Anderson *et al.*, 2011). To test the validity of this assumption, Feldon *et al.* (2011) implemented a controlled study of graduate students across science and engineering disciplines, comparing the skill growth of students who participated in supervised research and did or did not also have teaching responsibilities. Results indicated that graduate students with both research and teaching experiences demonstrated significantly greater skill growth in the areas of framing testable hypotheses and designing experiments. Growth in other research skills did not differ significantly between the groups, indicating that the benefits of both teaching and research activities did not hinder skill development in other aspects of research.

KEY ISSUES FOR FUTURE RESEARCH

The existing scholarship on training in the sciences predominantly utilizes a socialization framework (Gardner, 2010), in which socialization is defined as “a process of internalizing the expectations, standards, and norms of a given society, which includes learning the relevant skills, knowledge, habits, attitudes, and values of the group that one is joining” (Austin & McDaniels, 2006, p. 400). The society that doctoral students aspire to join is that of the scientists publishing and conducting research within their chosen discipline. Graduate students are expected to learn their new roles and with them, the requisite skills, values, attitudes and expectations, although the opportunities to do so are not necessarily equally available to all students (Weidman, 2010). These issues are further complicated in the context of interdisciplinary research endeavors, which require both graduate students and their faculty mentors to redefine traditional boundaries and disciplinary norms (Rhoten, 2004).

While valuable as means to highlighting many aspects of the doctoral student experience, and inequities within those experiences, previous research on graduate research training elides a crucial aspect of that experience: skill development. Skills are observed to develop, but there is little empirical evidence of how they are developed, whether or how their development varies across different groups of students, and in what ways they might contribute to other outcomes of graduate education, such as persistence and scholarly productivity. Those studies that do address skills generally examine feelings of preparedness for conducting independent research rather than measures of discrete skills (Delamont & Atkinson, 2001). As

demonstrated by the Feldon *et al.* (2015) study described previously, such self-report measures do not accurately predict demonstrable skills. Thus, establishing robust operational definitions for research skills and utilizing performance-based measures of skill development are essential for better understanding the mechanisms and enhancing the quality of expertise development in scientific research (Lovitts, 2007).

Understanding the interplay among experiences, motivation, and skills will also provide novel insights into reducing the observed inequity in research training outcomes. Women and minority populations are consistently underrepresented in many science disciplines. While previous research has considered inequalities in socialization experiences, skills represent a crucial missing link. If students from different sociodemographic groups enter their research training with differential levels of preparation and research experience (Kim & Sax, 2009), and if new skills build upon existing skills, this initial difference may produce growing inequalities in skill levels across different groups of students as they progress through graduate school (Feldon, Maher, *et al.*, 2016).

Further, identifying the experiences and training mechanisms that directly influence the development of specific research skills will provide a foundation for new training approaches. Despite burgeoning efforts to train graduate students to engage in interdisciplinary science, for example, empirical data regarding associations between practices and outcomes are almost nonexistent (Vanstone *et al.*, 2013). Various interventions and strategies already exist to address skill gaps and differential success in research training programs. For example, many “boot camp” interventions emphasize statistical data analysis skills. However, as discussed above, progressions of skill development seem to begin with the effective reading and use of primary literature and the ability to generate testable hypotheses (Kiley & Wisker, 2009; Timmerman *et al.*, 2013), with data analysis skills not developing until later on. Thus, it is not clear that early interventions targeting analysis would be effective or an efficient use of limited training resources. Understanding how skills are developed over time and how they interact with relevant motivational constructs can optimize the creation and implementation of training experiences that both maximize students’ skill development and reduce inequality by identifying the key predictors of success and the pivotal time points in the development of expertise in the sciences.

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