

Cumulative Advantage in the Skill Development of STEM Graduate Students: A Mixed-Methods Study

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Studies of skill development often describe a process of cumulative advantage, in which small differences in initial skill compound over time, leading to increasing skill gaps between those with an initial advantage and those without. We offer evidence of a similar phenomenon accounting for

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differential patterns of research skill development in graduate students over an academic year and explore differences in socialization that accompany diverging developmental trajectories. As predicted, quantitative analysis indicated large effect sizes for skill gains after controlling for initial performance levels. Qualitative analyses indicated that students with initial advantages were more likely to report greater demands of independence by their advisors and see more extensive value in research tasks comparable to those assigned their less skilled peers.

KEYWORDS: graduate education, research training, skill development, mentorship, socialization

The preparation of an effective and innovative scientific workforce is essential to the economic growth of the United States (Wendler et al., 2010). Further, the diversification of that workforce is considered an essential strategic priority for both the inherent value of diverse perspectives contributing to research and innovation and the leveraging of additional subpopulations to meet the growing workforce demand (Intemann, 2009). However, it is not only the number of scientists available to the workforce but also their research skill and ability to break new theoretical ground that is paramount (U.S. Department of Labor, 2007). Thus, the goal of graduate education is to prepare a highly skilled workforce, not merely a highly credentialed one, by helping students transition into scholars and producers of research (Weidman, 2010).

Substantial research on the development of graduate students as they earn their degrees and prepare to enter the workforce has utilized the lens of socialization to examine the 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). Core graduate student socialization processes include knowledge acquisition, investment, and involvement (Weidman, Twale, & Stein, 2001). Knowledge acquired consists of disciplinary attitudes, values, norms, and research skills—the bedrock of doctoral education (Golde & Walker, 2006). Investment refers to personal commitment toward the pursuit of a graduate degree. Involvement includes interactions with faculty mentors, peers, and other members of the disciplinary community in the immediate environment and beyond, such as those encountered at professional conferences. Of these, faculty mentor–graduate student interactions are considered most influential to student research skill development (Maher, Gilmore, Feldon, & Davis, 2013; Nettles & Millett, 2006; Parry, 2007; Wisker, 2005), with “interaction between faculty and students in a laboratory . . . frequent (daily) and often directive in nature” (Gumpert, 1993a, p. 265).

However, several studies suggest that the initial differences in students’ abilities and motivation influence the quantity and quality of mentoring they

receive. For example, Green and Bauer (1995) showed that the amount of mentoring provided during the first year could be predicted by students' incoming potential, including their attitudes, objective abilities, and research-related experience. This implies that the initial skills with which students enter graduate programs may be a strong influence on the course of the socialization process. Indeed, a longer term follow-up study reported that students' initial research experiences along with collaborative mentoring (defined as the extent to which the faculty mentor invited the student to coauthor on five different types of research projects, such as a journal article or grant proposal) measured at the end of the second year of the PhD program independently and positively predicted cumulative research productivity four years later (Paglis, Green, & Bauer, 2006).

Despite its importance, surprisingly little is known about skill development outcomes at the graduate level. Skills are assumed to develop as a function of graduate training and socialization opportunities. However, few studies assess skill outcomes as a function of student experiences, the sequence of their development, whether or how their development varies across different student groups, and in what ways they might contribute to other outcomes of graduate education, such as persistence and scholarly productivity (Feldon, Maher, & Timmerman, 2010).

Several types of skills have been identified as critical outcomes of graduate education in research fields, ranging from generic (e.g., teamwork, communication; Nyquist, 2002), which are arguably important in all fields of professional endeavor, to technical or bench skills (e.g., pipetting, spectroscopy; Atkinson, Delamont, & Parry, 2000) that are highly specialized within a subfield or even an individual laboratory. A third type of skill—methodological research skill—is generally applicable across scientific fields, but it has nuances specific to individual disciplines (Gilbert, Balatti, Turner, & Whitehouse, 2004). These include skills such as framing experimental hypotheses, designing experiments, and appropriately grounding conclusions in the data obtained. Collectively, skills in this category reflect the building of disciplinary arguments within empirical research fields, the mastery of which is considered an essential conceptual threshold for those pursuing advanced degrees in the sciences and engineering (Kiley & Wisker, 2009).

Evidence suggests that development of methodological research skills is contingent on prior development of other research skills, such as the ability to situate work in context using primary literature (e.g., Kiley, 2009; Timmerman, Feldon, Maher, Strickland, & Gilmore, 2013). Thus, the fact that students often enter graduate programs with highly variable skill sets and differing prior relevant experiences (Feldon et al., 2011) may set students on divergent trajectories of research skill development. For example, Gilmore, Vieyra, Timmerman, Feldon, and Maher (2015) found that first-year graduate students who had participated in research experiences as undergraduates demonstrate 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.

This issue is particularly concerning in the context of students from sociodemographic groups who may have systemically reduced access to or likelihood of engaging in undergraduate research experiences (Bangera & Brownell, 2014). In an analysis of undergraduate research participation by demographic group, Kim and Sax (2009) determined that this concern was justified. They found that African American, first-generation college students, and students from lower socioeconomic backgrounds were significantly less likely to participate in undergraduate research with faculty.¹

It is not known how these differences at entry to graduate science, technology, and engineering programs manifest in skill development over time. It is possible that early skill gaps close as a natural consequence of graduate training. It is also possible that gaps persist stably over time because graduate students tend to develop skills at a consistent or linear pace. A third possibility is that initial differences in fact compound over time, resulting in significantly larger gaps at later time points than at outset. The purposes of the current study are to (a) assess which of these possible trends best reflects observed patterns of research skill development and (b) characterize the differences in socialization experiences that students report as a function of their initial skill levels over a one-year period.

We first examine the extent to which levels of research skills assessed in early fall predict skill levels of initially stronger students and initially weaker ones at the end of the academic year (late spring) using performance-based data from a sample of graduate students in research-focused science, technology, and engineering programs. Using their initial scores as covariates to statistically control for preexisting skill differences at the outset of the study, participants' spring scores are compared to assess skill gain. If the skill gaps narrow over that time period, the dependent variables (spring scores) will differ significantly, and adjusted means will be higher for the initially weaker students. If the skill gaps remain stable, using initial scores as a covariate will result in nonsignificant differences between initially stronger students and initially weaker ones. If the skill gaps increase, the year-end score differences between the groups will significantly favor students with initially stronger skills sets. Following this analysis, we delve into qualitative data collected from the participants to better understand the nature of potential differences in socialization opportunities between students with initially stronger skill sets and those with initially weaker skill sets. Thus, our research questions are as follows:

Research Question 1: Do research skill gaps diminish, remain stable, or grow over the course of an academic year?

Research Question 2: Are initial differences in skill level predictive of the nature of students' descriptions of mentorship practice, the type of student research

activities undertaken, or students' perceptual changes in their research ability or researcher identity?

We hypothesize that improvements in students' research skills will be significantly greater at the conclusion of a single academic year for those participants entering the study with higher skill levels, even after statistically controlling for differences in initial skill levels. We further expect that the socialization experiences participants report will differ as a function of their initial skill levels during the same period.

Theoretical Framework

We situate this study within a socialization framework, which is commonly used in doctoral education (e.g., Gardner, 2010; Holley, 2009; Weidman, 2010). As noted previously, socialization occurs upon joining a specific group. For science, technology, and engineering graduate students, key membership groups likely include research teams, academic departments, and disciplines. Thus, graduate students simultaneously undergo a double socialization process as they acclimate to groups associated with both a graduate student role and a disciplinary member role. In this way, graduate school and disciplinary socialization are intertwined, sharing common agents, locations, and outcomes (Golde, 2010). As Green (2005) observes, "As much as anything else, the [faculty] supervisor represents, or stands in for, the Discipline itself" (p. 162).

Weidman and his colleagues (2001) describe graduate student socialization as occurring within stages, as do others (e.g., Gardner, 2009; Lovitts, 2001). Stage models are useful heuristics for identifying potential socialization challenges (Ashforth, Sluss, & Harrison, 2007). However, individuals are not passive recipients of unfolding socialization transitions. Rather, they "actively extract clues to their behavior and continually evaluate themselves in the context of peers, faculty mentors, program expectations, and personal goals" (Weidman et al., p. 18).

Socialization processes frame newcomers' interpretation of the meaning they make of their roles and tasks within the larger social structure (Ashforth et al., 2007). Ashforth and colleagues (2007) note that newcomers often give particular weight to the views of credible people, such as, in the case of graduate students, faculty mentors. In fact, for graduate students, the faculty mentor has long been considered the primary disciplinary socialization agent (e.g., Baird, 1995; Lyons, Scroggins, & Bonham Rule, 1990). Further, for graduate students in the sciences and engineering in particular, the faculty mentor's established areas of research inquiry and funding typically shape the nature and extent of his or her graduate student mentees' engagement with research activities (Golde, 2010; Neumann, 2007). Indeed, Gumport (1993a) articulated the American model of graduate education as

being fundamentally integrated with research in the sciences, technology, and engineering to attain both “the production of research and the preparation of trained research personnel” (p. 226). Thus, it is not surprising that faculty mentorship has been closely linked to graduate student research skill development (Paglis et al., 2006; Walker, Golde, Jones, Conklin Bueschel, & Hutchings, 2008). In turn, the nature and extent of graduate student research engagement has been linked both to students’ perceptions of their research ability (Delamont & Atkinson, 2001; Lyons et al., 1990) and their identities as scientists (Holley, 2009).

Further, newcomer adjustment is facilitated—or not—by early socialization experiences that also affect long-term outcomes. For example, when individuals fail to academically and socially integrate into their graduate programs, attrition often follows (Lovitts, 2001). Moreover, graduate socialization literature has highlighted ways in which access to different socialization opportunities is not the same for all graduate students. Overlapping contextual differences in departments, institutions, and disciplines matter (e.g., Austin, 2011; Gardner, 2010; Golde, 2005), as do individual differences such as gender and race (e.g., Noe & Ray, 2012; Sallee, 2011). These factors combine to shape student perceptions of their fit within their programs and the likelihood of persisting in them (Gardner, 2008). However, the effects of initial differences in students’ skills on subsequent socialization experiences have received little attention.

In many socially situated endeavors, including education, initial modest advantages lead to easier access to supportive resources and subsequently greater success (Rigney, 2010). Thus, small differences early on result in cumulative advantage that results in widening performance gaps (e.g., the development of reading skill; Baumert, Nagy, & Lehmann, 2012). Research is more limited in higher education—especially in graduate study. However, a recent study of 15 doctoral students in a research-intensive university described how graduate students who published early (typically as coauthors with their mentors) gained legitimacy and were given further opportunities to join new research projects and have greater interactions with faculty (Gopaul, 2011). Similarly, those participants who obtained federal funding early (i.e., National Science Foundation [NSF] graduate research fellowships) perceived that to be a major advantage in gaining and easily maintaining the positive perceptions of faculty. Likewise, the studies of graduate students’ access to mentorship and subsequent scholarly productivity reported by Green and Bauer (1995; Paglis et al., 2006) reflect significant future opportunities and outcomes associated with comparatively small initial skill advantages. It should be noted, however, that these studies examine publication outcomes, which are often the result of collaborations with faculty. As such, they are reflective of collective effort and cannot inform our understanding of research skill development within individuals (Feldon et al., 2010). The current study links

individuals' development of specific research competencies to their socialization experiences.

Methods

The current study employs a sequential explanatory mixed-method design (Creswell, 2013) in which both quantitative and qualitative data are collected. Quantitative performance data were analyzed first to differentiate initially higher performers from lower performers; year-end skill levels were compared between these two groups. Based on classification as initially more or less skilled, qualitative data, in the form of interview data for participants in each set, were analyzed to identify common and differentiating trends in perceived socialization mechanisms associated with the observed quantitative effects. In the current effort, qualitative data provide novel insight into how, within the day-to-day lived experiences of science, technology, and engineering graduate students, initial differences in research skill level foreshadowed socialization patterns.

Participants

Participants were graduate students in research-focused graduate degree programs in science, technology, or engineering disciplines recruited from three universities in the eastern United States as part of a larger NSF-funded study (see Feldon et al., 2011). They were recruited for the study at information fairs for incoming graduate students, through the posting of flyers on science, technology, and engineering department announcement boards, and via university e-mail distribution lists targeting science and/or engineering graduate students. Those who enrolled in the study received a participation incentive of \$500 for providing data during their year of participation. Prior to study enrollment, individuals were screened to ensure that they met the criteria for participation (i.e., full-time students with full tuition support and at least 10 hours per week of supervised research responsibilities), that they fully understood the expected scope of participation over the course of the academic year, and that they signed informed consent documents approved by the university Institutional Review Board. Of the 95 participants for whom full quantitative data were collected, our sample for the current quantitative and qualitative analyses consisted of 75 (male = 42) graduate students pursuing research-intensive degrees (MS and PhD) in various science, technology, and engineering disciplines (see Table 1). Excluded participants did not demonstrate sufficient strengths or weaknesses to be classified as "high performers" or "low performers" at study outset, per the method described in the Data Analysis section. Most were in their early years of graduate education, with 49 students in their first year of their respective graduate programs. Accordingly, most had two or fewer semesters of research experience prior to study participation.

Table 1
Distribution of Participants by Discipline, Degree Objective, and Year in Program

Year in program	Public Doctoral Institution			Large Master's Institution			Small Master's Institution						
	Master's			Master's			Master's						
	1	2	3	1	2	3	1	2	3				
Science	4	2	0	22	5	4	6	9	0	6	5	0	63
Technology	2	2	0	2	1	1	0	0	0	0	0	0	8
Engineering	6	2	0	6	6	4	0	0	0	0	0	0	24
Total	12	6	0	30	12	9	6	9	0	6	5	0	95

Data Collection

For each participant, quantitative and qualitative data were collected at two time points—the beginning of the fall semester (September) and the end of the spring semester (late April or early May) of a single academic year. All data were collected during a three-year period. Several data sources were utilized: written research proposals sole-authored by each participant, tests of scientific reasoning (Lawson’s Test of Scientific Reasoning and ACT Test of Science Reasoning), and individual interviews.

Research Proposals

To gain an authentic, performance-based measure of research skills, student participants submitted sole-authored research proposals for projects in their respective areas of interest early in the fall term of their participation year. They then revised and resubmitted their proposals in late spring of the same academic year. Participants were instructed to describe the relevant literature and design for their proposed research as well as anticipated results, other potential outcomes, and the significance of these in relation to their research questions or hypotheses. Rubric criteria include the following research skills: setting the proposed research in context; framing testable hypotheses; appropriately integrating primary literature; addressing validity and reliability of data; experimental design; selecting, presenting, and analyzing expected data; basing conclusions on data; and identifying alternative explanations and limitations of the proposed study.

The research team provided no feedback to the participants between the fall and spring submissions, though participants were free to seek independent feedback from other sources typical of their academic support networks and programmatic resources. Most participants reported informally that they used their proposals for an additional purpose beyond the research study itself, such as for classwork, research lab, or conference proposal. This information was interpreted as a positive indicator of both legitimate effort invested in the task and ecological validity (i.e., “conducted in settings that occur in the culture or subculture for other than research purposes . . . [including] place, time, roles, and activities” [Bronfenbrenner, 1976, p. 7]). Written proposals were anonymized, and each was scored by two raters using a validated rubric (for full descriptions of the rubric, its application, and its validation, see Feldon et al., 2011; Timmerman, Strickland, Johnson, & Payne, 2011) to generate numeric scores for each of 10 individual criteria. Intraclass correlations for initial scores from each rater on each criterion ranged from .60 to .90. Differing scores between raters were resolved through discussion to yield a finalized, single score per criterion.

Quantitative Control Variables

Participants completed pre- and posttests of scientific reasoning using two instruments. Performance on the 24 multiple-choice item Lawson's test reflects participants' abilities to draw deductive inferences from data and evaluate the control of variables in abstract scenarios (Lawson et al., 2000). The ACT science reasoning test is a 45 multiple-choice item instrument that draws content from biological sciences, chemistry, physics, and other physical sciences and requires students to (a) interpret tables, diagrams, and graphs; (b) critique experimental designs and conclusions; and (c) analyze empirical support for alternative hypotheses (American College Testing Program, 2005).

Prior research experience was quantified according to the number of semesters of research completed prior to study participation. For participants with nonacademic research experience, each four-month period was quantified as a semester.

Interviews

Fall interviews collected demographic and background information (e.g., number of years in program, prior research experience descriptions, expectations, and self-assessments). Spring interviews included questions asking for students' descriptions of the following during the preceding academic year: (a) relationship with faculty advisor, (b) nature and extent of engagement in research activities, and (c) perceived changes in research skill and/or researcher identity. These experiential and perceptual components were targeted because of their direct link to the graduate student socialization process, as noted earlier. Interviews were semi-structured and ranged from 30 to 45 minutes in length. With the participant's permission, each interview was recorded and transcribed verbatim.

Quantitative Analysis

Median scores for the fall proposals were obtained for the 10 criteria of the rubric used by independent raters to score the proposals. For each criterion, participants were classified as "low" performers if their scores fell below the median and "high" performers if their scores fell above the median. Classifications were summed to obtain the number of criteria for which each participant was classified as high and low. Participants with sums greater than 5 highs were classified as high performers ($n = 36$). Participants with sums greater than 5 lows were classified as low performers ($n = 39$). Twenty participants did not meet either threshold and were excluded from subsequent analyses.

Using Mplus version 6.1, multivariate analyses of covariance (MANCOVAs) were conducted in which fall criterion scores, duration of previous research experience, and scientific reasoning scores served as

covariates; spring criterion scores served as the response variables; and group (high vs. low) served as the independent variable. All response variable rubric scores had 1.1% to 2.0% missing data at the first time point and 14.7% missing data at the second time point. A missing values analysis ($\chi^2_{17} = 23.20, p = .14$) showed that the missing data met the assumption for missing completely at random (MCAR; Little, 1988). However, missing data were handled more conservatively under missing at random (MAR; Enders, 2010) assumptions using a maximum likelihood estimation algorithm to guard against Type 2 errors resulting from a loss in statistical power.

Data analyses were conducted in four steps. First, MANCOVA analyses enabled the direct statistical test of the null hypothesis that a given rubric score element mean difference (higher-scoring participants' mean minus the mean for the lower-scoring participants) was zero. Second, the analysis of 5,000 bootstrap samples of size $n = 75$ participants enabled the computation of 95% confidence intervals (CIs) for each rubric score mean difference. Third, Cohen's d effect sizes were computed for all mean differences. Finally, Monte Carlo analyses of 5,000 hypothetical sample data sets of size $n = 75$ participants enabled the determination of the number of times in 5,000 samples the null hypothesis of a zero mean difference for all rubric score elements was rejected.

Qualitative Analysis

Transcripts usable in qualitative analysis were secured for 68 of 75 (91%) participants. Transcripts were first categorized by fall proposal scores (high performers, $n = 32$ [47%]; low performers, $n = 36$ [53%]). Then, each transcript was read in total to holistically ground interpretive analyses. As noted previously, participant transcripts were originally collected as part of a larger study. Thus, transcripts contained responses to questions unrelated to the current effort but potentially informative in situating relevant responses within each participant's lived experience.

Using a constant comparison approach (Glaser, 1965), responses to questions about advisor relationship, research activities, and perceived changes in research ability and/or identity were closely scrutinized. Specifically, responses to these questions were constantly compared and contrasted across transcripts to identify thematic commonalities and differences both *within* and *between* the high and low performer category to identify if meaningful differences in descriptions of key socialization experiences and perceptions could be linked to category affiliation. The second author conducted all initial qualitative analysis. Subsequently, the first author independently reviewed all data and themes as a measure of interpretation trustworthiness. Divergence in interpretation between the authors was resolved through iterative discussion of identified transcript segments and derived themes.

Findings

Findings are presented by study research question and concordant method. First, to systematically test if initial differences in research skill diminish, remain stable, or increase over an academic year, we analyzed pre- and post-academic year student research proposal data. Then, we considered if and how initial advantage in research skill was associated with further advantage in critical graduate student socialization domains, including faculty advisor–student relationships, the nature or type of student research activities undertaken, or students’ perceptual changes in their research ability or researcher identity.

Trajectory of Skill Development

Do research skill gaps diminish, remain stable, or grow over the course of an academic year? After controlling for covariates, large effects indicating a greater magnitude of skill gain for initial high performers were obtained, as predicted by the cumulative advantage hypothesis. By criterion, the mean differences, effect sizes, percentage of the Monte Carlo population significant, and MANCOVA p values are presented in Table 2. Effects were significant for every criterion, and effect sizes ranged from Cohen’s $d = 0.54$ to $d = 1.01$, representing medium to large effects (per Cohen, 1988) of initial skill levels on later skill levels after controlling for the magnitude of initial differences between individuals. These findings reflect a widening skill gap between participants with differing levels of skill at study outset over the course of the academic year.

Socialization Experiences Associated With Higher and Lower Levels of Initial Skill

Are initial differences in skill level predictive of faculty advisor–student relationships, the nature or type of student research activities undertaken, or students’ perceptual changes in their research ability or researcher identity? Thirty-two student interview transcripts (14 provided by female students; 18 provided by male students) were categorized as receiving high fall proposal scores (“high performers”). Thirty-six student interview transcripts (17 provided by female students; 19 provided by male students) were categorized as receiving low fall proposal scores (“low performers”). The term *graduate student socialization* reflects a cumulative account of day-in and day-out experiences in ways both large and small. However, we target three: faculty-student relationship, the nature or type of student research activities undertaken, and students’ perceptual changes in their research ability or researcher identity that are essential to the development of a competent and autonomous researcher, largely recognized as the end goal of graduate education in the sciences (Austin, 2010; Delamont & Atkinson, 2001).

Table 2
Quantitative Results Identifying a Cumulative Advantage

	Mean (High)	Mean (Low)	<i>SD</i> (High)	<i>SD</i> (Low)	Mean Difference	Cohen's <i>d</i>	% Population Significant	<i>p</i> Value
Introduction	2.219	1.953	0.504	0.486	0.267	0.54	89	.029*
Use of literature	1.213	0.549	0.614	0.695	0.664	1.01	100	.001*
Hypotheses	0.833	0.392	0.453	0.532	0.442	0.89	100	.003*
Reliability	1.855	1.360	0.574	0.636	0.495	0.82	96	.002*
Design	0.702	0.261	0.471	0.444	0.441	0.96	100	.002*
Data selection	0.226	-0.170	0.430	0.588	0.396	0.77	100	.008*
Data analysis	0.660	0.173	0.573	0.601	0.487	0.83	100	.006*
Data presentation	-0.509	-0.976	0.643	0.873	0.467	0.61	100	.026*
Conclusions	2.624	2.265	0.697	0.582	0.359	0.56	100	.032*
Limitations	4.477	3.969	0.775	0.546	0.508	0.76	100	.005*

* $p < .05$ (one-tailed).

Faculty-Student Relationship

We begin with the nature of the relationship between the faculty advisor and his or her graduate student, widely thought to be the most important relationship to graduate student development (Barnes & Austin, 2009; Walker et al., 2008). Almost without exception, high performing students described a very favorable relationship with their faculty advisor. The single exception was a student report of an annoyed advisor who was “getting to the point where she needs me to take charge and make more decisions” (Participant 2435, female). Although two advisors were described as “busy,” most high performing students characterized their advisors as “supportive,” “helpful,” and “very involved,” as illustrated by comments such as, “I’ll send him an e-mail and he’ll answer me at 9:30 on a Saturday night” (Participant 8135, male); “I’m very grateful my advisor is as helpful as he is; I wouldn’t have been as successful with my project if he hadn’t been” (Participant 8110, female); “She is always there to answer questions and is very helpful” (Participant 6362, male). Three (male = 2) reported an advisor relationship in which interactions included a personal element, saying, for example, “He [advisor] often invites us [research team members] to his home for dinner” (Participant 3054, male). Of note, many positive characterizations were noticeably coupled with references for work expectations, such as “He [advisor] will help you out, but he’s holding me at the level of a post-doc position . . . you know, seventy hours a week” (Participant 2485, male); “Our relationship is good but in the beginning, it was a proving ground type of mentality” (Participant 6142, male); “He’s a friend to me as much as he is yelling at me to get work done in the lab” (Participant 4510, female). Several student descriptions of advisor interactions included expectations for student self-direction, including:

My advisor doesn’t really want to give me the answer; he wants me to find out on my own. (Participant 6152, female)

My advisor is approachable, but you want to have an idea of why you are asking the question and he wants you to try to figure it out on your own first. (Participant 6132, female)

He is very supportive, but he wants me to become a better scientist. That involves some challenges and some frustrations, but that is part of the process. (Participant 6152, female)

If you need his help he’ll be right there, but there’s a lot of independence involved. There is not someone holding your hand. There is definitely a lot expected of you. (Participant 8145, male)

I’m very independent which is sort of his style of being an advisor . . . he expects I will figure it out, then I bring to him what I have and he critiques it. (Participant 8165, female)

In addition, several high performing student descriptions suggested a relationship in which the student perceived his or her advisor trusted or valued his or her contributions as a peer:

She [advisor] trusts me with the work I had wanted to do and told me that no one has ever done some of the experiments I did this semester. (Participant 9050, female)

The topic, since it is so new, I can find out as much as she [advisor] can, so it is very much an equal playing field and she really likes the ideas that I have and bring to the table. (Participant 2070, male)

My advisor was very receptive to my ideas as far as new data or what we can do; I thought we had equal footing. (Participant 6362, male)

Descriptions of faculty advisor relationships offered by low performing students initially mirrored their high performing student counterparts. Only one low performer described a troubled advisor relationship, saying his advisor was “difficult to relate to” (Participant 1989, male). The remaining described a positive advisor relationship. Advisors were characterized as “supportive,” “motivating,” “patient,” and “dedicated.” While five low performers described their advisor as busy, most described a close relationship, as illustrated by comments such as, “If it is a Sunday at 8 pm I can [still] call him up and get his advice” (Participant 9006, male); “She’s there to guide me” (Participant 3032, female); “He’s very accessible” (Participant 4916, female); “We work very closely” (Participant 2136, male); and “He came to the lab every day to ask students about research progress” (Participant 2080, female). Six (all males) reported an advisor relationship in which interactions included a personal element, represented in comments such as “He [advisor] is more like a guardian, like a father” (Participant 2415, male); “I think he looks at me as if I am his son” (Participant 2040, male); “He also talks with me about my personal things” (Participant 2030, male); and “He teaches me how to survive in the United States” (Participant 2055, male).

Further, several descriptions of advisor interactions and expectations indicated that students in this category perceived their advisor to be fairly flexible with research commitments:

He [advisor] will never tell you, “Come on the weekends; you have to do the research now.” (Participant 1479, male)

He [advisor] takes care of me and is understanding of my other time commitments. (Participant 2360, male)

I actually expected a little more structure because he [advisor] is like, “Just work on this stuff and get back to me.” I was expecting, “You need to have this done!” (Participant 8140, female)

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He [advisor] just expects you to do your work well. If you want a break and you've worked hard, that's okay. He doesn't expect you to come in at a certain time or report to him at a certain time. (Participant 1898, female)

Almost all students, regardless of initial research skill level, enjoyed a positive relationship with their advisor. Both high and low performer categories contained an abundance of advisor-student relationships described as close, with most advisors perceived as approachable, available, and ready to assist students' research efforts. All participants reported that their advisors expected them to engage in research activities.

In general, however, advisors of students categorized as high performers were reported to hold higher expectations for student dedication to research productivity and for student self-direction. These advisors conveyed to their students the perception and expectation that they were more advanced researchers who either already possessed or could quickly learn requisite skills, in some cases, treating these students as equals in the research process. Conversely, advisors of students categorized as low performers were reported to be slightly more flexible in their expectations for student research productivity and autonomy. Further, participants' comments indicated that they were more likely to communicate a perception to students that they are beginning researchers who perhaps needed to grow into their research role.

Research Activities

As noted earlier, all students, regardless of program entry research skill level, described engagement in research activities. Eleven high performing students (male = 6) reported that their advisor was the only person involved in their research activities. Four of the 11 reported coauthoring a conference paper and/or journal article as a result of their research activities. Eight reported starting or contributing to research projects for which they reviewed primary literature and collected and analyzed data. Advisor meetings were frequent. Most appeared to have extensive control over the topic and design of the research in which they participated. For example, one high performing student stated, "I'm looking at habitat utilization by predatory fish in estuaries. My advisor has a lot of background in that . . . but he's in no way telling me what to do" (Participant 8145, male). Another recounted, "I'm focused on writing my thesis proposal. . . . I have a lot of control over what I want to do . . . my advisor just advises me on how feasible it is" (Participant 8100, female). Occasionally, these efforts were marked by false starts and mistakes. For example, one high performing student recalled:

What I was attempting . . . was not working. We [advisor and I] could not get any extracted DNA . . . so we bagged that idea. (Participant 2685, female)

I made a horrible, horrible mistake. . . . I had to come in and dose mice and I asked the lab technician about the mercury, and she said, "Oh, just read the bottle." I misread the bottle and ruined my experiment. I wanted to ask her more specifically, but she was really busy and I didn't want to bother her and it led to 15 mice dying. (Participant 2445, female)

Twenty-one high performing students (male = 14) reported participating in research activities with others in addition to their advisor, including undergraduates, peers, postdoctoral fellows, other faculty, and/or professionals from industry. The size of collaborative grouping ranged from very small (e.g., the student, advisor, and one postdoctoral fellow) to very large (e.g., "I think there are a total of seven [graduate students] in the lab right now" (Participant 6132, female). Research activities included reading primary literature and other background materials, performing learning laboratory techniques and software/database management, sometimes in collaboration with others, but often, as one student reported, "There is always some collaboration, but we always have our own projects" (Participant 6132, female). Fourteen reported coauthoring a conference paper and/or journal article with individuals other than their advisor as a result of their research activities. While collaboration was recounted, independence and leadership were constant themes in descriptions of research activities. Representative comments from high performing students included:

I don't have time to talk, "Oh, what do you think I should do?" I have to go in there [laboratory] with a plan and do it, so it has forced me to be more independent with my ideas. (Participant 6132, female)

My advisor has been so busy that she's been like, "Here's a grant. Write it. Here's a paper we need to do next week. Write it." (Participant 2435, female)

I designed a big chunk of the experiments we did this semester and came up with what we needed, so it became more like I was a leader, not a follower. (Participant 9050, female)

The lab as a core works on the main project and I have taken a piece of that as my dissertation. I would say I do 90% of that work, and other people help out on other stuff, but I'm the primary mover of those data. (Participant 2485, male)

They [mentor and labmates] came out with the research problem and I read it and took a look in the literature and came up with the idea to implement those techniques, so actually it is my design to implement those techniques on that research. (Participant 2060, male)

Sixteen low performing students (male = 7) reported that their advisor was the only person involved in their research activities. These students'

research activities were often marked by isolated laboratory or field work coupled with regular advisor meetings. Students recounted reading primary literature and other background materials, collecting and analyzing data, and discussing their progress with their advisor; six reported coauthoring a conference paper and/or journal article as a result of their research activities. Descriptions of research activities included:

I read the literature and discuss it with my professor. We come up with experiments, what to do, what not to do, what controls to use and how to interpret the data, how to go about the experiments and, depending on the results, discuss again how these results can happen. (Participant 2030, male)

We meet for about an hour each week and I tell him what I've done and then we make plans for the next week. It helps make sure I'm going down the right path. (Participant 2035, male)

I had to spend a lot of time in the lab [and] I was finding a lot of cultures and I could use these cultures in my tests. (Participant 7171, female)

The majority of students who worked solely with their advisor reported that their advisor retained most or all control over the subject and design of the research in which they participated:

I am doing something completely different [from my undergraduate research topic]. It is difficult for me to apply all that I have learned to this new topic so I am just following my advisor and he is teaching me everything by himself, [saying], "Ok, this is the first step, this is the second step." (Participant 3043, male)

The big decisions are decided by my advisor and I will do the detailed work. (Participant 2055, male)

All I had to do was watch this screen. We had these mice. I counted how many squares they crossed in five minutes. I know it is important to do that type of research, but it was totally not for me. (Participant 7649, female)

Despite the aforementioned, students who worked solely with their advisor also commonly reported making mistakes:

I was doing the experiment for two or three weeks and wasn't getting any results. In the end, the pH I wanted was 10 and I had 8 pH. Such minor mistakes happen. (Participant 2030, male)

I make some very big mistakes with some of the reactions that can be really expensive, and I can sense that he [advisor] is angry but he never says anything to me. If I haven't done the experiment before,

I'll ask him a lot of questions over and over again to make sure it is OK. (Participant 3043, male)

My research didn't go anywhere in the beginning but by trying things and failing at them . . . I feel has helped me recognize what to do now and how to do it. (Participant 9006, male)

I was doing a lot of mistakes. I understood by myself now after doing those mistakes and after knowing what I was doing wrong. (Participant 9012, female)

Twenty low performing students (male = 12) reported participating in research activities with others in addition to their advisor, including undergraduates, peers, postdoctoral fellows, other faculty, and/or professionals from industry. The size of collaborative grouping ranged from very small (e.g., the student, advisor, and one industry collaborator) to very large (e.g., the student, advisor, and "many students, graduate and undergraduate, and a new PhD, so it's a lot," Participant 2045, male). Two attended programs requiring lab rotations and moved from laboratory to laboratory, changing collaborators as they did so. Research activities included reading primary literature and other background materials, learning laboratory techniques, and software/database management, usually in collaboration with others. Four reported coauthoring a conference paper and/or journal article as a result of their research activities. Besides lightening the workload, these collaborators appeared to supplement a student's reliance on his or her advisor for guidance:

I keep on asking questions and that way the PhD student would say, "If you do it that way, this will go wrong" so he would tell me in advance. (Participant 2045, male)

I focused on learning how to manipulate the instruments and just focused on the experiments. Working with the post-doc on my team has helped me very much. He has done a lot to let me know more about this field. (Participant 2465, male)

I have another teacher [postdoctoral fellow] to collaborate with. We talk very often about the research. I go to his office and we discuss a lot and I know better about the methods for research. (Participant 2520, male)

I knew when I came to this program my advisor would be busy. I do not go to him for small questions. First, I ask the other graduate students. (Participant 2380, female)

My advisor and other graduate students show me the way to familiarize me with the techniques. (Participant 4916, female)

Cumulative Advantage in Research Skills

Research activities also included attending team research meetings, which provided an opportunity for novice students to learn from more advanced team members:

Listening to other group members' presentations, listening to the stuff they do, hearing their problems and their issues allows me to apply it too, thinking, "Ok, I could do it this way next time and I might get a better result." (Participant 4916, female)

Talking with colleagues during research group [has helped me become a better researcher]. (Participant 2380, female)

I do much of the work but I get a lot of help from people around. We meet together. (Participant 2075, male)

Seeing other people do research—how they approach problems . . . talking with other graduate students and post-docs and so on [has helped me to be a better researcher]. (Participant 2455, male)

Both high and low performing students reported being involved in research activities over the course of the previous academic year. Research activities common across categories included literature review, data collection and analysis, and meeting with advisors and/or research team members. A little less than half (44%) of students categorized as receiving low fall proposal scores reported working only with their advisor, while about a third (34%) of those categorized as receiving high fall proposals scores reported doing so. Roughly the same percentage of students in each category reported coauthoring a conference paper or journal. When students worked solely with their advisor, control over research topic and design and making mistakes appeared to differentiate between categories, with those categorized as receiving high fall proposals scores reporting more control and fewer mistakes than their counterparts.

For those students in both categories who reported that their advisor *and others* were involved in their research activities, reports of coauthoring activities notably differed. Twenty percent (4/20) of low performing students reported coauthoring a conference paper or journal article with their advisor and/or others, while 67% (14/21) of high performing students did so. Other differentiating themes included the place of independence and leadership; low performing students who collaborated with others often appeared to use these interactions to supplement their reliance on their advisor. In contrast, high performing students who collaborated with others often appeared to use these interactions as a springboard to advance progress on their own individual part of the larger team efforts. Additionally, while the low performing students appeared to use team meetings to learn from more advanced team members, high performers reported acting as equal collaborators in or even leaders of these meetings more often.

Research Skill and Identity Change

At the end of the academic year, most high performing students perceived themselves to have become increasingly competent researchers, expanding their knowledge and skills. Hard work and personal characteristics were attributed for this success. Thus, self-descriptions such as the following were common:

I'm a pretty strong researcher. I'm only a first-year but in talking with some of the other students, I feel that I've done a lot more research than some of the others. (Participant 6132, female)

I'm pretty determined and hard-working and creative. I work with what I've got and if I don't have what I need I either get it or ask for it . . . I get a little determined when it comes to everything. (Participant 9050, female)

I've got a much broader sense of research now than I had before and am just building a very good skill set as now I have worked on all these things. (Participant 6162, male)

I've learned a lot of new techniques and I've gotten myself a lot of different options I can do as a researcher so I've enhanced my capabilities. (Participant 6362, male)

When I feel passionate about my research, I can really work hard. I see that I can be successful with it. (Participant 2060, male)

In contrast, at academic year's end, most low performing students perceived themselves to be novice researchers, using descriptors such as "greenheaded" (Participant 3043, male), "behind the curve" (Participant 2136, male), and "slow" and "fumbling along" (Participant 9015, female). Most, however, perceived they had experienced meaningful research skill growth in the past year and had become more competent as a researcher. Positive development in research skill and researcher identity was attributed to hard work and patience:

I've grown a lot more patient because I learned this [research] is a process. You don't get the results that you expected. So we keep changing experiments and you do it over and over again. (Participant 2075, male)

Just hard work [has helped me be a better researcher]. I work hard on the weekends too. (Participant 2390, male)

I spend a lot of hours in the lab. And sometimes it takes a lot of time and effort, and sometimes you get nothing. (Participant 9003, female)

Additional research experience also was perceived as contributing to research skill and identity development:

Initially I wasn't very confident because I didn't have that experience in hours [in the laboratory] so over time I think I've got the confidence. (Participant 2045, male)

I think just spending more time on the same thing because I came here last year and I had just started. Now it has been one year. I am just trying to get the basics of everything I'm doing, but I understand why I am doing things. (Participant 1599, female)

Initially, the analyses looked scary, but I am breaking them into parts and doing everything stepwise and trying to be professional. (Participant 1989, male)

Thus, most students in both categories perceived that they had experienced meaningful research skill growth in the previous academic year and had become more competent as researchers. Hard work was attributed across both categories as contributing to this growth. However, students categorized as earning lower fall proposal scores consistently described themselves in terms of still needing to develop skill and confidence as a researcher. Those categorized as earning higher fall proposal scores were much more likely to describe themselves as coming from a position of strength or confidence and were more likely to refer to their various successes throughout the year as evidence to support these self-perceptions.

Discussion and Conclusion

The present study examines patterns of science, technology, and engineering graduate students' skill development that may differ as a function of their initial skill levels. The findings indicate a robust cumulative advantage effect, in which demonstrable skill gains over the course of an academic year were significantly greater for those students who began participation in the study with scores above the sample median of research skill compared to those with scores below the sample median, after statistically controlling for those initial differences and differences in the extent of prior research experiences. Put another way, all other factors held equal, the participants whose initial scores were higher demonstrated a steeper growth trajectory than those whose initial scores were lower, resulting in a widening skill gap between the two groups over the course of an academic year. This gap in research skills is of particular note in the context of STEM graduate programs because research is essential to these disciplines as a core endeavor and as a key component of many careers requiring a graduate level of education.

This finding in and of itself might be expected, as the cumulative advantage effect has been demonstrated to exist in a wide variety of social and educational contexts (Rigney, 2010). Faculty advisors who perceive higher levels of skill (justifiably or not) may be more likely to assign tasks—especially important or challenging tasks—to those students, thereby creating

accelerated opportunities for future skill development and scholarly productivity. However, the qualitative data associated with our findings provide unique insight into the mechanisms that might drive this phenomenon in science, technology, and engineering graduate programs.

Prior research suggests that students who demonstrate greater academic promise at the outset of their programs will receive more attention from their advisors and greater opportunities to conduct research and publish (Green & Bauer, 1995). However, the findings presented here suggest that these interactions may be more nuanced. Participants in the current study did not report experiences in which they appeared to gain or lose access to mentorship or research opportunities. Regardless of whether participants had initially higher or lower research proposal scores, most reported strong, productive, and positive relationships with their mentors. Further, similar proportions of participants in both groups reported coauthoring with their mentors.

However, the nature of the experiences reported by these groups differed meaningfully in two ways. First, the level of independence with which participants engaged in their work reflected differences consistent with initial levels of research skill. Consistently, low performing students described their research collaborations with their mentors as collective endeavors in which they were heavily dependent on their mentors for accomplishing their goals: “I am just following my advisor and he is teaching me everything” (Participant 2035, male), “Big decisions are decided by my advisor” (Participant 2055, male), and so on.

In contrast, high performing students emphasized the facets of their work that required their independence—even when it was forced on them by their mentors: “My advisor . . . wants me to find out on my own” (Participant 6152, female), “You want to have an idea . . . he wants you to try to figure it out on your own first” (Participant 6132, female), “He expects I will figure it out, then I bring to him what I have and he critiques it” (Participant 8165, female).

The second difference observed between the two groups reflects divergent ways in which participants derived meaning from the specific tasks they were assigned as part of the research process—especially those perceived to be simple. Low performing students described their tasks in very generic and simplistic terms that were not explicitly connected to larger research goals for themselves or their mentors’ research agendas: “All I had to do was watch this screen. We had these mice. I counted how many squares they crossed in five minutes” (Participant 7649, female); “I focused on learning how to manipulate the instruments and just focused on the experiments” (Participant 2465, male).

In contrast, high performing students framed similar tasks in ways that were more extensive, linking to future steps and outcomes that were valuable: “They [mentor and labmates] came out with the research problem and I read it and took a look in the literature and came up with the idea to implement

those techniques, so actually it is my design to implement those techniques on that research” (Participant 2060, male), “The lab as a core works on the main project and I have taken a piece of that as my dissertation. I would say I do 90% of that work, and other people help out on other stuff, but I’m the primary mover of those data” (Participant 2485, male).

The mechanism that drives these observed differences is not clear. It is possible that the independence and active relating of assigned tasks to larger goals of high performing students are due to preexisting personality or dispositional characteristics such as beliefs about the basis of talent (e.g., Dweck, 1999, 2006) that lend themselves to greater rates of skill acquisition. It is also possible that the initial differences in skill level differentially position high performing students to feel confident acting with greater autonomy in their supervised research settings and to more readily recognize potential value in their experiences, as often expected by senior faculty (Campbell, 2003). This confidence could lead to greater investment of effort and a concomitant increased rate of skill development. A third possibility is that the mentoring styles of faculty members foster either increasing independence or dependence, which in turn lead to the differential rates of skill development observed. This last explanation could reflect either stable styles of mentorship enacted by individual faculty or an adjustment of expectations to attune to the perceived abilities of the student in question. Finally, some combination of these mechanisms may play a role, dependent on personalities and environmental affordances. Regardless of which explanation might be borne out by future research, the findings presented highlight the salience of initial skill level as an important factor in predicting widening gaps in graduate student learning outcomes, in addition to scholarly productivity. They also indicate that the nature of mentoring interactions associated with these differences are more subtle than simple differences in mentorship access or relationship quality.

Implications

The current findings have several valuable implications for the practice of graduate education. First and foremost is the importance of recognizing the variability in research skills with which students enter doctoral programs and the consequences of that variability. Socialization theory, which has been the primary lens for studying graduate education, in principle recognizes the importance of skills. However, skills have not received extensive or, in our view, adequate attention in terms of either objective measurement or attempts to equalize them. While graduate students are a highly select group, they nonetheless enter graduate programs with a wide range of skills. As our findings illustrate, these initial differences are associated with important consequences for students’ graduate experiences and subsequent performance. However, these experiences are not likely to be uniform, even for individual

students. As quoted by Gumport (1993b), “according to students, some days are better than others: ‘Some days you’re a peon. Other days, you’re king for a day’” (p. 265). Thus, understanding the experiences associated with initial skill differences over time provide direct insight into the differentiating socialization mechanisms at play in the lives of early career graduate students.

Given the importance of research skills for the STEM disciplines and many of the career options associated with them, the challenge for those charged with educating the next (and hopefully more diverse) generation of scientists and engineers is to develop strategies to address differences in skills with which students enter graduate programs. On the surface, study findings indicate that “skill inequality” differs in its manifestation from other forms of inequality, such as those reported by women and racial/ethnic minorities pursuing doctoral education (e.g., Taylor & Antony, 2000). Notably, gaining access to involved, caring mentors and building close interpersonal relationships with them are not, at least in this study, the obstacles faced by students who enter graduate education with lower levels of skills. However, if, as noted previously, mentors (consciously or not) are changing their style to accommodate student research skill deficits, their behavior does, in fact, mimic that recorded in studies of gender and racial/ethnic minority inequities. For example, in their study of successful socialization of African American doctoral students, Taylor and Anthony (2000) suggest that optimistic advisor student relationships are required but not sufficient; these relationships must be coupled with clearly conveyed advisor expectations that challenging scholarly work will be accomplished without the assumed need for extra help. This suggests that the initiatives focused on improving access to and socio-emotional quality of mentoring will not be sufficient for addressing skill inequality.

Once the importance and uniqueness of skill inequality are recognized, the challenge for practitioners is to develop strategies to address differences in skills with which students enter graduate programs. Given limited research in this area, our implications are largely speculative and rely primarily on practices targeted at undergraduates, as colleges and universities have paid more attention to skill differentials at that level. Although speculative, these implications present useful starting points for developing innovative interventions and studying their impact.

On the undergraduate level, it is well understood that high school academic preparation is one of the strongest predictors of college success (Adelman, 2006), and this is the case even at selective institutions that admit a relatively highly academically prepared student body (e.g., Bowen & Bok, 1998). Undergraduate institutions have recognized these differences and have adopted a range of strategies to address skill inequality, two of which are relevant to the discussion of graduate programs.

First, undergraduate institutions have tried to intervene through developing a range of transition programs and services as well as support mechanisms as

students progress through college. These can take various forms, from summer transition programs to learning communities. While evidence on these endeavors is not always encouraging (e.g., Barnett et al., 2012; Inkelas & Soldner, 2011), they aim to remedy wide gaps across a range of different skill sets.

Doctoral programs, which can focus specifically on research skills as opposed to trying to remedy a wide range of differentials, may be more effective. In recent years, for example, some doctoral programs in social sciences have started to require students to attend statistics boot camps, recognizing that students enter doctoral programs with widely different skills in this area, which can substantially disadvantage their progression through the program. In terms of developing research skills in the sciences and engineering, several studies imply that there is a progression of skill development, namely, that certain skills need to be mastered before other skills can be learned (e.g., Kiley & Wisker, 2009; Timmerman et al., 2013). Although this research is nascent, it suggests that programs could be structured to teach students specific research skills and do so in a particular sequence. This could potentially be accomplished through a combination of a summer experience before entering the doctoral program and required coursework during the first year.

The second way that undergraduate institutions have tried to reduce skill differentials is by reaching out to the institutions preceding them in the educational pipeline, including high schools and community colleges, to build common understandings of skills required for college success. Doctoral programs could engage in similar initiatives with undergraduate and master's programs by building partnership to facilitate the development of skills needed to succeed in doctoral programs. These endeavors may be particularly consequential for facilitating the success of students from racial/ethnic minority groups and socioeconomically disadvantaged backgrounds, who have less experience conducting research during their undergraduate years. Our findings imply that reducing the variability in skills with which students enter graduate school may help to equalize students' experience in graduate school as well as their subsequent development of research skills.

Finally, our findings have possible implications for broadening research and practice beyond a narrow focus on the mentoring relationship. While mentoring is a crucial component of doctoral education, the current study suggests that having an involved and accessible mentor is not a challenge faced by students who enter doctoral programs with lower levels of skills. Although coauthorship with their primary mentors is equally likely for students who enter doctoral programs with different levels of skills, substantial differences appear when considering coauthorship that involves researchers other than the mentor. Future research needs to explore the processes through which these differences emerge and identify prospective practices or interventions that could compensate for inequitable access to such opportunities. Is it that faculty, bound by the duties implied in the mentoring

relationship, invest and work with their advisees regardless of the skill level but do not recommend them for collaborations with other scholars? Or perhaps other researchers, not bound by the mentoring relationship, are more sensitive to skill differentials? These differences are only likely to be amplified as students progress through the graduate program, making it crucial both to understand how they emerge as well as to reduce their occurrence by equalizing skill levels among doctoral students.

Notes

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¹Outcomes reported in Kim and Sax (2009) differentiated between research interactions with faculty as a volunteer, for course credit, and for pay, so trends in significant differences varied slightly by category.

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