Artiles *et al.*
International Journal of STEM Education (2023) 10:6
https://doi.org/10.1186/s40594-022-00392-6

International Journal of
STEM Education

RESEARCH Open Access

Doctoral advisor selection processes in science, math, and engineering programs in the United States

Mayra S. Artiles[1*], David B. Knight[2] and Holly M. Matusovich[2]

Abstract

Although advising relationships are key for doctoral student success, little research has addressed how they form. Understanding the formation of advising relationships can help contextualize their later development and ultimately support a student's decision to persist in the doctorate. To understand relationship formation, the purpose of this qualitative study is to identify and describe the types of advisor–advisee selection processes that exist in engineering, science, and math doctoral programs and examine patterns across disciplines within those fields. We conducted interviews with doctoral program directors and engaged in document analysis of graduate student handbooks from 55 doctoral programs in the aforementioned fields in high research institutions across the United States. Using principal–agent theory as a theoretical lens, our findings showed that engineering programs tend to decentralize the advisor selection process by funding students across different funding sources upon enrollment. Contrariwise, science and math programs tended to fund all students in a cohort from a common funding source, which allowed students to have more time to gather information, meet, and select an advisor. These findings also show important nuances when comparing graduate education in these programs that directly impact the doctoral student experience and reiterates the necessity to study these fields separately.

Keywords Advisor selection, Graduate education, Qualitative secondary analysis, Doctoral students

Introduction

The relationship between a doctoral student and their advisor is the foundation of the student's success in completing a Ph.D. (Bair & Haworth, 2004; Barnard & Shultz, 2020; Barnes & Austin, 2009; Burt et al., 2016; Devos et al., 2016; Gardner, 2010; Hilmer & Hilmer, 2007; McCray & Joseph-Richard, 2020; Noy & Ray, 2012; Schlosser & Gelso, 2001; Zhao et al., 2007). Few studies, however, have focused on how these relationships form and, specifically, the facilitation role that doctoral programs play in this process. To help students match with the best possible advising relationship, we need to examine how students currently find their advisors and how departments help to facilitate this process (Golde, 2005; Nettles & Millett, 2006). Understanding this role is critical, considering that not all disciplines hold the same traditions and practices (Gardner, 2009; Golde, 2005; McAlpine et al., 2020).

The doctoral experience is often more likely to resemble others in the same discipline across institutions than other doctoral programs within the same institution (Becher & Trowler, 1989; Biglan, 1973; Hammond, 2005; Muller, 2009); (Goldman & Massy, 2001; Lattuca & Stark, 2009). Multiple theoretical frameworks suggest that people and their actions are a product of their environments (Edwards et al., 1998; Kristof, 1996; Weiner,

*Correspondence:
Mayra S. Artiles
mayra.artiles@asu.edu
[1] The Polytechnic School, Ira A. Fulton Schools of Engineering, Arizona State University, 7171 E Sonoran Arroyo Mall, Mesa, AZ 85212, USA
[2] Department of Engineering Education, College of Engineering, Virginia Tech, 345 Goodwin Hall, 635 Prices Fork Rd, Blacksburg, VA 24061, USA

1985), and research in doctoral education has been no exception. Numerous studies have shown how departmental and disciplinary differences influence the experiences of doctoral students and faculty advisors (Ferrer de Valero, 2001; Hopwood & McAlpine, 2007; Torka, 2018). Consequently, doctoral advising relationships are also influenced by the environment in which they take place (Zhao et al., 2007). In particular, their formation is a process that is also facilitated by the department in which it takes place (Golde, 2005; Nettles & Millett, 2006), often through a process documented in the graduate student handbook. Thus, we contend that to help students to identify their best possible advising relationship, we need to examine how they currently find advisors.

The purpose of this qualitative study is to identify and describe the types of advisor–advisee selection processes that exist in science, math, and engineering programs and examine patterns across fields of study and disciplines. We define disciplines as subdivisions of fields of study (e.g., engineering is a field of study, and mechanical engineering is one of its disciplines). We focus on science, math, and engineering fields because the advising relationship has been demonstrated to be critical, as the advisor and student often work in close collaboration (Zhao et al., 2007). Using principal–agent theory (PAT) as a theoretical lens (Eisenhardt, 1989), we address the following questions:

- What advisor selection processes exist across doctoral programs in a sample of science, math, and engineering disciplines?
- How do these advisor selection processes vary across disciplines?

The primary data for this study consist of interviews with doctoral program directors and the programs' handbooks disseminated to doctoral students. Understanding advisor selection processes can offer insight into doctoral students' early socialization into the department.

Advisor selection processes

The advisor selection process is often influenced by disciplinary traditions (Goldman & Massy, 2001). Some programs assign students to an initial, temporary advisor until they find a permanent advisor, while others negotiate the selection of an advisor through the admissions process before initial enrollment (Joy et al., 2015). The advisor selection process, while influenced by disciplinary traditions, is often managed by the doctoral program under the constraints imposed by both the department and institution (Joy et al., 2015; Sowell et al., 2015). As few studies have focused on these disciplinary differences and how students find an advisor, our study aims to fill this gap by describing the existing processes and their variations by academic disciplines, specifically in a sample of disciplines in science, engineering, and math.

Although research is rich with information about doctoral advising relationships, less is known about how these relationships form or how doctoral programs guide students and faculty in these processes. Instead, prior work has typically reported what students look for in an advisor. For example, two key studies compared student preferences across disciplines. By evaluating differences in advising styles across disciplines, Zhao et al. (2007) demonstrate that students in the sciences tend to select an advisor on the pragmatic benefit of that relationship over intellectual compatibility or a given advisor's reputation. Similarly, Golde and Dore (2001) show that doctoral students tend to select an advisor based on an intellectual match or research interests; the larger the number of factors that students considered when selecting an advisor, the higher their satisfaction with their advising relationship in the long term. Joy et al. (2015) also explore advisor selection processes in science, math, and engineering programs at a large research institution in the U.S. Midwest. According to Joy et al. (2015), students mostly focus on funding availability and research interests and, secondarily, on the advisor's personality and accessibility. The faculty perspective in the same study showed that faculty members focus on student credentials, such as grade-point average or standardized test scores, and students' ability to contribute to the faculty member's ongoing research. While this study provides key information on doctoral advisor selection, the study was based on a single institution, conflated multiple science, math, and engineering programs under the assumption that their processes were the same, and lacked analysis regarding the programs' influence on the selection process.

To our knowledge, no prior study has analyzed the selection process itself directly and comparatively in science, math, and engineering fields across a large sample of institutions. This gap is what we intend to understand further through this study. Some studies have focused on these processes with a direct look into specific disciplines. Regarding the selection itself, Schlosser et al. (2003) demonstrate that students value the ability to choose and tend to select advisors with whom they believe they can work comfortably and successfully; these students reported being happier than students who were assigned to their advisor. Within science, technology, engineering, and mathematics (STEM) fields, Crede and Borrego (2012) argue that doctoral engineering programs are distinctive from other fields of study because of the organization into research groups such that the advisor selection process also influences the selection of students' closest work colleagues. While this prior study only focused on doctoral engineering students, the practice of research groups has also been studied in disciplines within the sciences. Maher et al., (2020a, 2020b) show that students in biosciences doctoral programs evaluate a series of criteria during their rotation periods, such as mentoring style, professional stability, research projects, and peers in the research group. However, in a separate analysis, the authors also demonstrate that behaviors exhibited in the rotation period may not be a perfect representation of daily doctoral life (Maher et al., 2020a), a common phenomenon in doctoral recruitment (Slay et al., 2019).

Outside of the U.S. context, not much research has described how students and advisors pair. Yet, there is some insight into what students value in a search for an advisor that aligns with findings from the United States. For example, Onen (2016) highlights examples in the Ugandan context that show how students both value agency in deciding with whom they will work while simultaneously feeling inadequate and lacking support to make this decision. This is similar to findings of some of the prior work in the U.S. context (Artiles & Matusovich, 2022a). In the case of students traditionally minoritized in higher education, Grant (2010) describes how Māori students in New Zealand prioritize advisor identity in the selection process, specifically as to whether the advisor could be trusted to properly guide their research in relation to Māori epistemology and research topics. From the faculty perspective, faculty in a Canadian study shared similar values in recruiting students, describing how they primarily relied on intuition as a criterion when selecting which doctoral students they offered a position to (Denis et al., 2018). These findings speak to the broader value of trust in an advising relationship that Robertson (2017) highlights as critical in advising scenarios (specifically for those who do co-advising). Ensuring success based on trust can be a gamble for both students and faculty. Considering this body of work, we conclude that both within and beyond the U.S., both students and faculty still value having agency in their advisor selection process and often have to resort to non-tangible factors in this decision process that relies on trust. However, the specific factors considered and weight assigned to these factors are not always consistent and will inevitably vary across individual preferences, fields of study, and disciplinary traditions.

Admissions and onboarding into the doctorate

Advisor selection is often connected to the admissions processes of a doctoral program, making it difficult to separate the two. For example, first contact is typically when students reach out to faculty members before admission in an effort to learn more about the program or find information about potential funding sources (Noy & Ray, 2012). These first contacts can have consequences on admissions and advisor selection processes. For example, research has shown that professors are often less likely to respond to emails from students whose names suggest them to be female or from a traditionally underrepresented group (Milkman et al., 2012). Similarly, Borrego et al. (2021) showed that it is often this first contact through admission that dictates the funding mechanism that students are offered. However, this process is often unclear to students and limits their agency in what mechanism (e.g., teaching or research assistantship) they are offered, which could have important implications on their subsequent opportunities within their program and beyond (e.g., Grote et al., 2021; Kinoshita et al., 2020). Prior work has also shown that students rely on both formal and informal networks to decide who they want their advisor to be (Maher et al., 2020b), which puts women and certain minoritized students at a disadvantage as they are often isolated in doctoral education (Posselt & Grodsky, 2017). As if these networking barriers were not enough, traditional measures of success in graduate admissions in STEM often lean towards quantitative measures of performance, such as standardized test scores and grade-point average, which have been shown to not be the best measures of success towards degree completion (Posselt, 2015; Posselt et al., 2019; Scherr et al., 2017) and systemically discriminate against underrepresented students (Miller et al., 2019; Weeden et al., 2017).

Yet, despite these barriers, other modes of recruitment and admission processes have been shown to help to diversify the applicant pool and provide support structures in the onboarding process for students. For example, Rudolph et al. (2019) and Moreira et al. (2019) show that bridge programs could help students to reframe their future academic experiences and help participants to have an easier time adapting and succeeding within the doctoral programs. Similarly, Posselt et al. (2018) show that policy changes, even when unintentional, can expand diversity during recruitment. Thus, analyzing existing admissions policies and practices can be a productive activity for understanding potential impacts on the advisor–advisee selection process.

Concerning onboarding, not much research has addressed this part of the process as it relates to advisor selection. We are unaware of literature that describes a typical onboarding process in doctoral education, but some work describes student preferences in what the process should allow. Polmear and Simmons (2020) studied one research group's onboarding practices and found that onboarding is a team activity in which all students

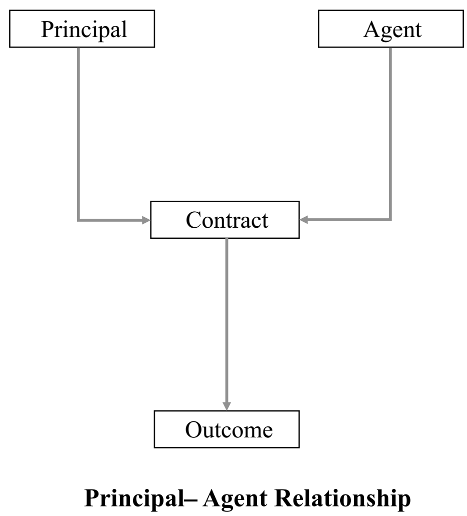

Fig. 1 Diagram of principal–agent relationship

participate, which represents a way to perpetuate the group's culture. This practice allows the culture to self-sustain, develops the group's sense of community, and enables positive communication around shared expectations. Two studies of early doctoral students highlight how incoming students value this explicit clarification of roles and responsibilities as well as provision of support (Guillaume et al., 2020; Hayles, 2021). Such clarity and access alleviate students' anxiety when entering a doctoral program. While these activities and preferences are described as occurring after admission and possibly selection, we argue that they should be embedded in the selection process as they can help students to be informed of what working with any given faculty member will ultimately entail in practice.

Theoretical underpinnings

This study is grounded in PAT (Shapiro, 2005), which posits that there is a principal who desires a task to be done, an agent to whom the principal outsources the task, and a contract that stipulates conditions for the completion of the task (Shapiro, 2005). The agent and principal are bound to each other by a contract that leads to an outcome (refer to Fig. 1). The goal of PAT is to determine the relationship between the principal and agent based on the contract conditions that classify a contract either as behavior-based or outcome-based.

PAT states 10 propositions that describe the contract between an agent and the principal; these propositions describe how information is shared between the principal and agent, what tasks are requested in the contract, the distribution of risk, and how the contract develops over time. How these elements are managed will determine if a contract is behavior-based or outcome-based. In contracts that are behavior-based, the principal specifies behavior for the agent to perform as they complete the task. In contracts that are outcome-based, the principal requests a specific outcome from the agent without regulating their behavior throughout the completion of the task.

PAT has been predominantly used in higher education research to study the relationship between the government and higher education administration (Lane, 2012). However, some newer studies have focused on the institutions' interactions with students. For example, Lozano and Hughes (2017) use PAT to study how student representatives in governing boards act on behalf of the student body's interests. Similarly, Dill and Soo (2004) argue that this theory helps to represent inefficiencies in how students select institutions and courses. Closer to the topic of graduate education, through the lens of PAT, Flora (2007) synthesizes the legal arguments on whether graduate students are employees of the university or not. There is still much room to grow in applying this perspective within higher education research, particularly in studying interactions between faculty and students in academic programs. Further, theories stemming from economic traditions can provide insight into what human behavior one can expect from certain scenarios (Thaler & Sunstein, 2008). Therefore, our study moves forward from the traditional uses of PAT by using it as an interpretive means for the interactions occurring between students and faculty members in doctoral programs.

Based on the theoretical definitions, in this analysis, we propose that the principal consists of the faculty members leading the program (as they represent the organization), and the agent is the student. The desired outcome for both the program and student is the selection of an advisor. The contract consists of established rules for the advisor selection process; as such, a behavior-based contract refers to those processes that structure how the student will make the advisor selection, and an outcome-based contract will be a scenario without a set of structured rules for making this choice. Using this operationalization, we examine the practices, as described in interviews and handbooks, regarding how to find an advisor to analyze how information is shared between parties, what tasks must be completed before selection, the distribution of risk between faculty members and students in the program, and over how much time the contract process takes place. Analyzing this information about the advisor selection process through the lens of PAT as described by Eisenhardt

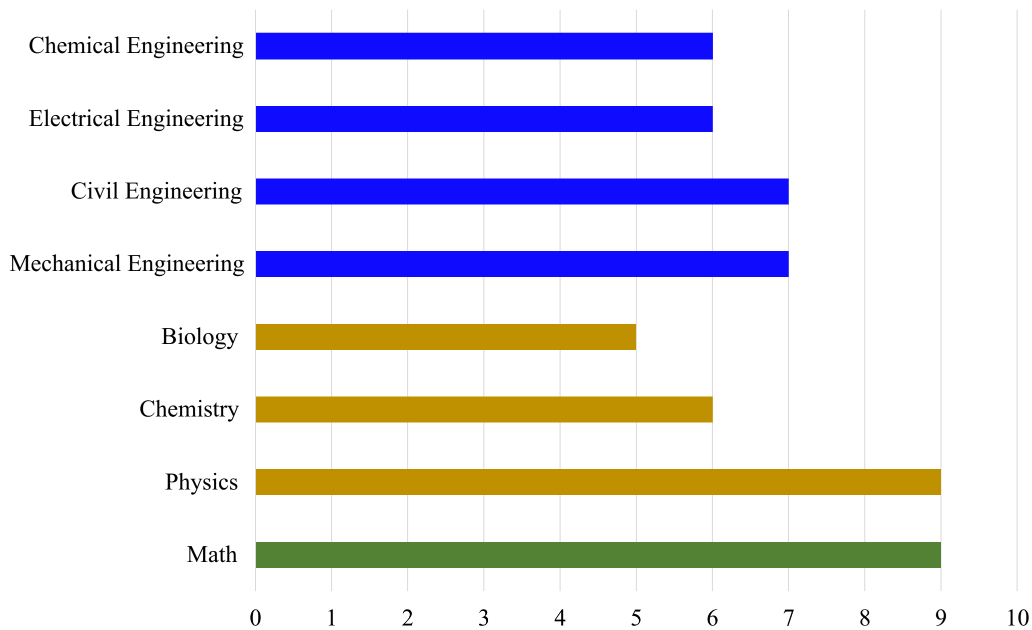

Fig. 2 Number of doctoral programs per discipline

(1989) provides a new way to interpret existing advisor selection practices.

Methods

This study was grounded in supplementary secondary analysis method (Heaton, 2004), which refers to an approach whereby an emergent aspect of previously collected data was not fully addressed in the primary study and is investigated in-depth (Heaton, 2004). Our study consisted of two main data sources: (1) previously collected semi-structured interviews with graduate program directors of multiple Ph.D. programs, and (2) student handbooks that describe the rules of each Ph.D. program of the interview sample. By using both data sources, we were able to obtain a holistic view of the process as practiced in each program.

Data

This study was conducted in accordance with approved human subject research protocols. The interviews used in this study originated from a different study [de-identified for review], where the main objective was not to understand the advisor selection process but rather how programs strategize about the allocation and distribution of graduate student funding in science, math, and engineering doctoral programs. Although the original objective of these interviews differs from that of the current study, these interviews ask the question, "How do students find advisors in your program?" as well as follow-up questions on the advisor selection process as practiced in the sampled doctoral programs. These responses were used to capture features of the process that may not be available in the graduate student handbooks. Interviews were held between the Fall of 2017 and Spring of 2018.

The main unit of analysis for this study was the doctoral program—our study included an analysis of 55 U.S.-based doctoral programs in the fields of science, math, and engineering in high research institutions, as defined by the Carnegie classification system (Shulman, 2001). Figure 2 summarizes the programs by counts per discipline. The disciplines are not a complete sampling of all science, math, and engineering disciplines but a purposive sample of those disciplines with large enrollments. The institutions are a combination of private and public institutional control and were sampled from across the country for geographical variety.

We complemented the interviews with a document analysis (Leech & Onwuegbuzie, 2007) of the advisor selection process as written in the graduate student handbook or equivalent for each program. These documents were obtained via a search of the programs' websites or through an email request to the program coordinators. The combination of these two data sources helped to identify the formal advisor selection process practiced in the program, exceptions or variations to that process, and information regarding the process that would not typically be documented in a graduate student handbook. We paraphrased the original handbooks so that the programs remain un-identifiable.

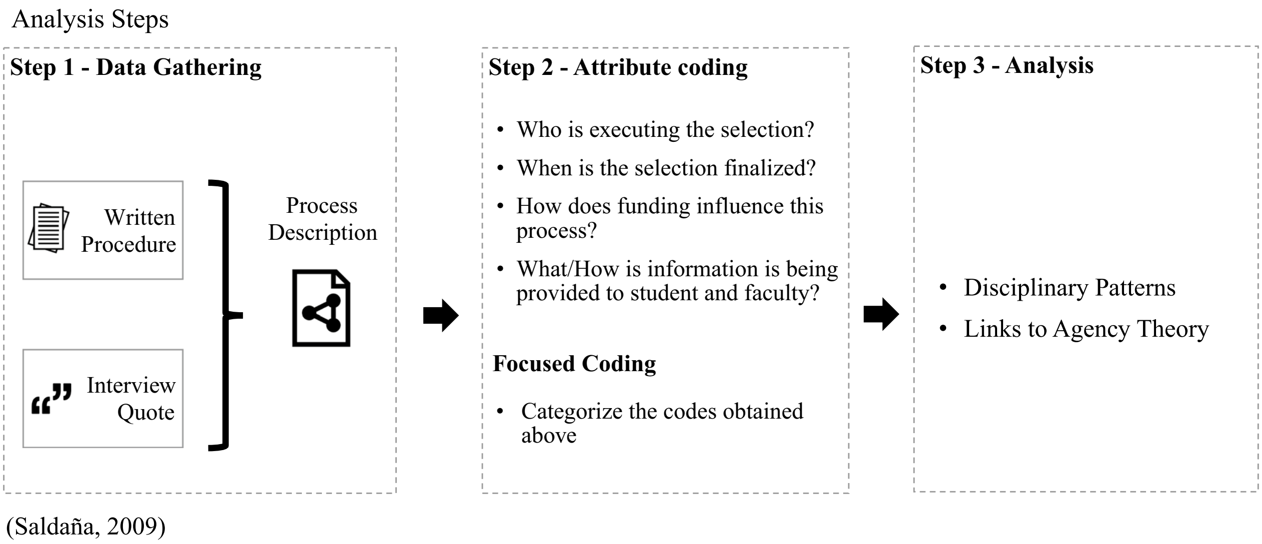

Fig. 3 Qualitative data analysis steps

Data analysis

We used PAT as a lens to understand the process that guides the formation of advisor–advisee relationships. Studying how these processes compare across disciplines provides insight into the policies and practices of doctoral programs. Our process consisted of three steps: data preparation, coding, and analysis (refer to Fig. 3).

Using a pragmatist worldview (Lincoln & Guba, 1985), we first developed a full characterization of the processes found in each program by comparing the two data sources, interviews and handbooks, thus building on both formal and informal components of the process. Open attribute coding (Miles et al., 2014) of the resulting full characterization of processes yielded four emergent dimensions of the advisor selection process: (1) who is making the selection of the advisor, (2) the timelines for the selection, (3) the information provided for the selection, and (4) the influence of funding in the selection process. We then conducted focused coding within each of these dimensions (Miles et al., 2014), which helped to collapse the attributes data into emergent subcodes of discrete categories within the dimensions. The themes resulting within each dimension as a function of the focused coding allowed us to infer analogous relationships between the PAT elements and the emergent dimensions of advisor selection processes in the assessed programs. Finally, the findings of such coding were analyzed for disciplinary patterns. Table 1 displays the codebook used for the analysis and includes examples of how data were coded.

Research quality

Our findings were generated as described above and were then triangulated between both data sources to ensure that the process was not misinterpreted from any one source (Tracy, 2010). Although we found no cases of an explicit contradiction between the interviews and handbooks, there were some programs where single source of data did not provide enough information to fully understand the process, reiterating the need for using both the interviews and handbooks. The approach and findings were audited by researchers both within the original project from which the interviews were sourced and outside of the project to ensure that multiple vantage points were being considered when interpreting findings (Heaton, 2004).

Limitations

The main limitation is that this study used a sampling of doctoral programs in science, math, and engineering that did not include all the disciplines within these fields. Therefore, any conclusion obtained from this secondary analysis is limited to the sampling scope of the original study. In addition, the data only provided the viewpoint of the program director and what they believe the program does to help students to find advisors as well as the handbooks that they develop for students and faculty. This view represents strictly the perspective of the program and may not reflect the experiences of other faculty members and graduate students, which are discussed elsewhere (de-identified for review). Similarly, the described process focuses on the most typical practices for each program. While on

Table 1 Analysis coding process

Emergent dimensions from attribute coding	Sample emergent focused codes	Analogous PAT element
Who makes the choice?	• Student and Advisor • Program Director	Identify Principal and Agent in each Process
Is funding available before selection?	• Faculty during admission; student only accepts or declines offer • Yes, not attached to advisor selection • No, attached to advisor selection • Depends on source offered in the admission letter	Process Constraints
When is the Selection Made?	• During admissions/enrollment • By 1st semester • By 2nd semester • Before third year • Depends on initial funding mechanism • No timeline specified	Length of the Contract between Principal and Agent
How is information shared prior to the selection?	• Research Seminars • Interviews • Independent Study • Rotations	Existing Information Systems between Principal and Agent

no occasion did the interviews explicitly contradict the manuals, the interviews did provide occasional examples of exceptions to the process. For these instances, the programs were classified by the processes experienced by the majority of their students as described in the interviews. Further research should look at these other perspectives and exceptions to the common practice to further understand what occurs in departments.

Findings

Advisor selection processes consisted of the following four elements (as shown in Fig. 4): (1) the selection process, (2) the role of funding in the selection process, (3) the timing of the selection relative to student enrollment, and (4) the information systems available to students before the selection of an advisor. The patterns in relationships between the four elements are highlighted with arrows (see Fig. 4).

Programs were first constrained by selecting how students and advisors find each other. This selection process was further constrained based on the program's funding model. By constraining the first two elements, programs then had a timeline range within which they require a decision. Finally, this timeline determined which information systems could be implemented. The following sections dive deeper into each element and describe the distinct patterns by disciplines and fields of study.

Selection process

Each program in our sample can be classified distinctly into one particular type of process, which varies in how the selection is made and structured: (1) students and advisors self-select without the program intervention, (2) programs assign a temporary advisor and then students and advisors self-select, and (3) formal matching, which is completed by the program, assigns students to advisors.

In the first type of process, the student and advisor have complete control over the selection process and are free to select whomever they want to work with. The program does not intervene in the selection outside of establishing a deadline by which a relationship must be formalized. The following handbook excerpt describes the process in a Civil Engineering Ph.D. program:

> *"Our program does not have a formal matching process by which students are assigned to advisors. We allow the process to happen organically, and for this to work properly, students must reach out to faculty to identify mutual interest."*
> *[Civil Engineering, Graduate Student Handbook]*

This self-selection process was found to be the most common across all programs in our study.

In the second type of process, students are assigned a temporary advisor, after which they can select a different faculty member if they choose to do so. The temporary advisor helps with the initial guidance, and students are given a period of time to formalize an advising relationship, which may or may not be with the temporary advisor. For example, a chemistry program director explained this practice:

> *"We poll them in the summer for their preferences and give them a temporary home in a lab based on space available. [...] Usually, what happens is they'll join their temporary lab, but we really push them*

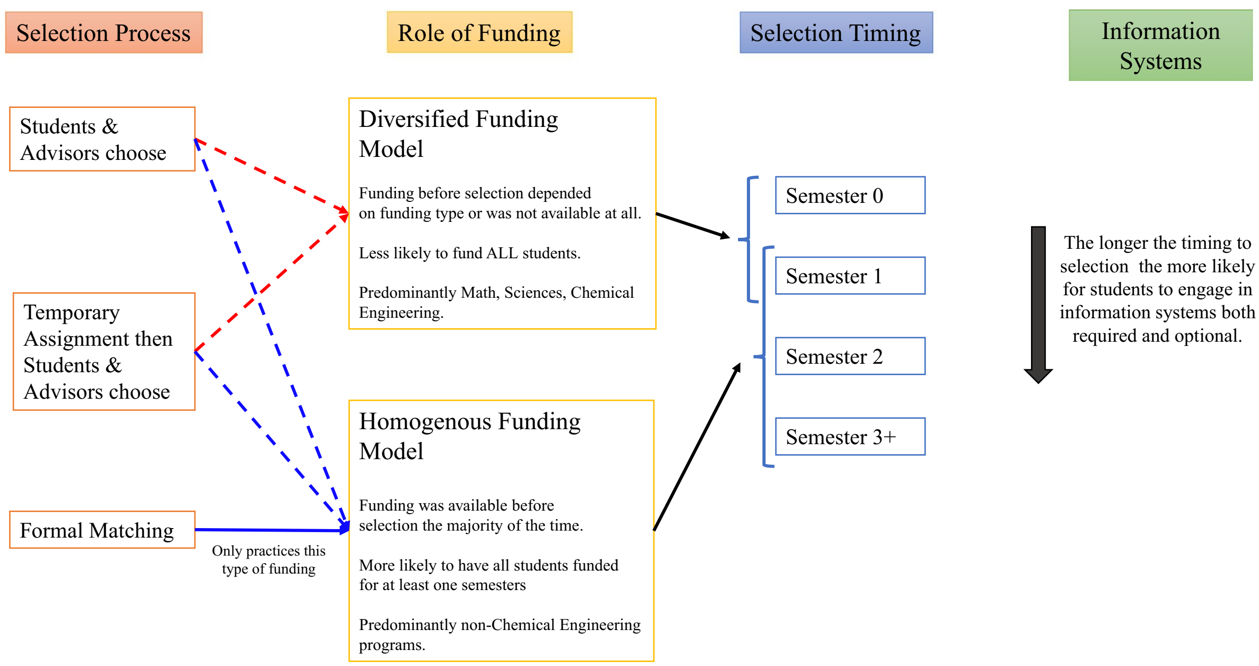

Fig. 4 Main components of any advisor selection process

> *to go to seminars and group meetings, talk to grad students, interview faculty as much as they can and then commit around Thanksgiving."*
> *[Chemistry, Program Director Interview]*

Although students and advisors had an option to not remain in the temporary advising relationship, students who chose to change advisors were not always guaranteed funding along with the switch. Thus, changing advisors may entail a search for funding, potentially limiting a student's mobility within a program. This process was mostly found in civil engineering, mechanical engineering, and some programs in science and math.

The third type process is where programs conduct a *formal matching* process with faculty and students. In this process, programs provide funding for their students through an initial enrollment period of either one semester or one year. During this time, students are expected to meet with potential advisors and determine their preferences. Similarly, faculty members are encouraged to meet with potential advisees and decide who would be a good fit for them and their research projects. On a predetermined date, students submit their top choices for an advisor to the program coordinator. The program director then collects faculty members' preferences—typically informally—and uses these two sets of information to 'match' students and faculty members. A program director described this process:

> *"All of the students will go to these presentations, and then they'll have a few weeks to meet with faculty members to have more in-depth discussions, attend group meetings, do lab tours, talk with graduate students. Then we collect a form from all of the students, listing their top three or four choices. Those get turned into the graduate studies committee. Usually, the chair takes on most of the responsibility. By the end of September to October, they should be matched with a faculty advisor". [Chemical Engineering, Program Director Interview]*

This formal matching process was the most common in chemical engineering, chemistry, and biology. In sum, we found three main types of processes through which students find an advisor. Within each of these processes, we observed variations in the funding models, selection timing, and information systems available to students. The distribution of the processes across disciplines and fields of study is presented in Table 2 via counts of the programs within each type of selection process.

Role of funding

We found two main models for funding management relative to the advisor selection. In the diversified funding model, students within the same cohort are initially funded through a diverse set of mechanisms, such as research assistantships, teaching assistantships, or fellowships. Students' processes to select their advisor are based on their funding source. For example, students

Table 2 Types of selection processes

	Students and Advisors	Temporary advisor, then Students & Advisors choose	Formal Matching
Engineering	Electrical – 6 Mechanical – 5 Civil - 3	Mechanical – 2 Civil - 4	Chemical – 5
Science	Biology – 3 Chemistry – 3 Physics - 7		Biology – 1 Chemistry 2
Math	Math – 7	Math – 2	

1 = disagree, 2 = rather disagree, 3 = rather agree, 4 = agree (that personal requirements were met);

N = listwise deletion

who were funded via teaching assistantships or fellowships (both internal and external) had time to evaluate an advising commitment prior to making a final selection; however, students in the same department who were funded via research assistantships directly by a faculty member often had an expectation for continuance in such projects and, by consequence, a commitment to selecting that faculty member as their advisor. The following quote describes how one electrical engineering program practiced this diversified funding model:

> *"If a new graduate student has accepted a research assistantship offer, the advisor is the faculty member who offered the assistantship. A new graduate student that is self-funded is usually assigned an advisor for the first semester. If both the student and the advisor are satisfied with this relationship, the relationship can be formalized." [Electrical Engineering Program, Ph.D. Student Handbook]*

As not all students enter with the same funding source or the same set of expectations relative to their funding, the advisor selection experience will be different across students. Some students enter with an advisor already selected, while others enter with time to decide before committing to an advisor. Programs that practice this diversified funding arrangement were less likely to fund students before they selected an advisor, and they were less likely to fund all doctoral students upon admission. None of these programs practiced the formal matching process, as that would require all students to be funded at least in the first semester without committing to an advisor. Most disciplines that used this funding model were engineering disciplines, with chemical engineering being a notable exception. Fewer than three science programs were classified as practicing this funding model.

In the homogenous funding model, all students within an incoming cohort receive the same funding conditions for the initial selection period, and all students may select an advisor under similar selection conditions. In practice, this model is described as an entire cohort, starting their studies funded by the same funding sources (typically the department) until they formalize an advising relationship, typically by a prespecified deadline. Math and science programs commonly assign their incoming cohorts to teaching assistantships, as these departments house introductory math, physics, and chemistry courses that are traditionally high service in most institutions. These programs often do not admit enough doctoral students to cover their teaching assistantship needs. An abundance of this funding source allows programs to guarantee funding until the students find an advisor, as explained by one physics program director:

> *"A typical student would be funded as a [teaching assistant]. We have these big general physics classes, and we have various flavors of them. Mainly, one course for engineers, one for pre-meds, and then there's a lab course that a lot of these teaching assistants work in. Once they find a thesis advisor, they would be funded as a research assistant." [Physics Program, Program Director]*

Even when the department did not count on courses that provided a large number of teaching assistantship positions, programs practicing this funding approach would aim to fund students through an initial period, even for just one semester, before the students selected an advisor. All chemical engineering programs practiced this model. The central idea of this homogenous funding model is that all students have equal conditions in their first semester before they select an advisor. Programs that practiced this model were more likely to have all students funded before selecting their advisor and were more likely to fund all students throughout their studies. Programs that practice the homogenous funding model were found across all three types of advisor selection processes.

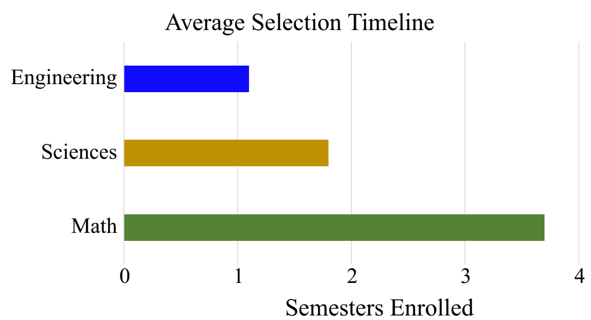

Fig. 5 Average selection semester per field of study

Selection timing

Depending on the departments' funding model, we observed different patterns for the selection timing. Programs that practiced the diversified funding model tended to have their advisor selection occur early in the doctoral program and never beyond the first year of study. All engineering programs in the sample required students to select an advisor by the beginning of the second semester but, sometimes, as early as before a student's matriculation. Programs in the sciences, on average, required students to select an advisor by the end of their first year, but on occasion, some programs did not require a formal selection until past that initial year. Finally, programs in math required students to select an advisor on average by the end of the second year, but on occasion, students were allowed to continue studying without a formal advisor until their third year. These patterns match our prior classification of diversified versus homogenous funding models, as programs in the math and sciences were more likely to fund students for an initial period of time prior to selecting an advisor, while engineering mostly had students decide prior to enrollment or quickly thereafter (see Fig. 5).

Information systems

Many programs developed informational activities so students could obtain information that would promote an informed advisor selection. For the engineering programs (chemical engineering being the exception), activities were typically optional and often non-existent. In chemical engineering, sciences, and math, activities were a requirement for students prior to committing to an advisor. The five activities typically included: (1) research seminars, (2) one-on-one interviews, (3) rotations, (4) summer research, and (5) independent study courses.

Research seminars were the most common form of an information system for students to become familiar with the available research projects while meeting the program's faculty. For example, a research seminar was described in one program handbook as follows:

> *"There are numerous opportunities for students to get to know potential advisors. This includes having them as teachers in introductory classes, attending the Invitations to Mathematics lecture series, regular research seminars, and colloquia (see Events), or self-development through academic advisors, peers, and publicly available research information." [Math Program, Graduate Student Handbook]*

The second most common form of an information system is ***one-on-one interviews*** with faculty members. Many programs encourage students to meet with advisors before committing to an advising relationship, and some require students to meet with a minimum number of faculty members before selecting an advisor. A program handbook describes the required interviews as follows:

"Students must meet with at least three faculty members. The meetings will be verified on a departmental signature form." [Chemistry Program, Graduate Student Handbook]

The third type of information system common in the sciences is ***rotations***. Students are required to conduct a specific number of rotations through different research groups to test advisors, fellow lab members, and research topics before making a final selection. This type of information system was mostly present in biology and chemistry programs and was often, but not always, a requirement. Rotations were described in a handbook as follows:

> *"All graduate students are exposed to different groups through a series of rotations. Rotations serve various functions. Everyone has the opportunity to explore various laboratories, to find the laboratory where they will do thesis work. Ideally, one will explore different sub-disciplines and techniques relating to their main interest. Each rotation gives the student a place for contact with faculty and other students. Students are required to complete three lab rotations." [Biology Program, Graduate Student Handbook]*

The fourth type of information system is summer research prior to enrollment. This system was mostly found in the sciences, and it offered students the opportunity to begin their doctoral program a summer early as a way for students to experience research groups prior to commencing coursework. A handbook described summer work as follows:

> *"In some cases, students are fairly certain about what they want to do and who they want to work*

> *with when they arrive, and they have already spoken to a prospective advisor. For these students, it is very important to begin work with that group either in the summer before they arrive, or during their first year." [Physics Program, Graduate Student Handbook]*

The fifth type of information system common to math and physics is the independent study course. In these arrangements, students are expected to take an independent study or 'reading course' with their potential advisor before they commit to working together. The course typically consists of reading and discussing literature or faculty posing problems to observe students' approaches to solving these. The course is described in a handbook as follows:

> *"Students can trial faculty and topics by taking various reading courses with prospective advisors. The one-on-one nature of a reading course may also serve as a test of the advisor–advisee interaction in future thesis work." [Math Program, Graduate Student Handbook]*

In summary, most of these activities were practiced, and to a certain extent, required in the science and math programs but seldom required within engineering. These findings align with our prior finding of funding models, as the timing of this selection affects whether programs provide such information systems for students. The longer the time to the advisor selection, the more likely programs are to provide information systems that help students do their due diligence in selecting an advisor.

Discussion

We found three main types of selection processes through which students can find advisors: (1) students and advisors self-select, (2) temporary advisors prior to the permanent advisor, and (3) program-brokered formal matches. The processes varied in their connection to funding, timing selection, and the ways to make information available to students before selection.

Comparing across fields of study

Our main observation is that engineering programs, except chemical engineering, decentralize the advisor selection process by funding students across different sources from day one, which we describe as the diverse funding model. This model forces students to make an advisor selection earlier to ensure funding continuity, limiting the potential implementation of informational activities that could help students select an advisor. Conversely, science and math programs are more likely to fund all students within a cohort under equal conditions upon enrollment, which we describe as the homogenous funding model. This model allows students to have a longer time before selecting an advisor and consequently allows programs to offer informational activities or requirements that students should accomplish before that selection.

These findings align with a study from Knight et al. (2018) that used Survey of Earned Doctorates data to show that doctoral programs in the life and physical sciences fund higher percentages of their students through teaching assistantships than engineering, which funds more of their students through research assistantships. The engineering advisor selection process, being both early and based on pragmatic factors, also aligns with previously mentioned studies (Joy et al., 2015; Zhao et al., 2007). Due to the apparent connection between funding portfolios and advisor selection processes in our work that vary by field, departmental resources should be considered when contemplating doctoral advising. If, for example, colleges of engineering find that consistent problems arise between students and their advisors, one of the contributing factors to misalignments could be the timing of the advisor selection, which ultimately appears to link to funding. Findings also potentially connect to those of other studies that have shown math and certain science doctoral students to have a longer time to degree than most engineering students (Ferrer de Valero, 2001; Sowell et al., 2008)—with a longer time to select an advisor, students in these fields may not begin their dissertation research as early as students in engineering programs. However, it is important to consider how these onboarding activities that lead to an informed advisor selection can relieve student anxiety about the doctoral pursuit (Guillaume et al., 2020; Hayles, 2021), a critical consideration given that recent work has highlighted the perils of graduate student mental health (Levecque et al., 2017).

Through the lens of principal–agent theory

When analyzing our findings, we find connections to both the principal–agent relationship as well as the contract that binds them. As described by Eisenhardt (1989), a contract can be characterized on a spectrum between behavior-based, where the principal is primarily concerned with the process through which the agent reaches the outcome, and outcome-based, where the principal is primarily concerned with the outcome and not the process. We notice in our findings that programs in science and math tend to practice a behavior-based type of contract, whereas engineering programs tend to practice an outcome-based type of contract.

Eisenhardt (1989) notes that the more tasks are programmed into a contract, the more likely this contract would be behavior-based instead of outcome-based. We observe the presence of such tasks in math and science programs in the form of information systems, such as activities and requirements that students have to complete prior to selecting an advisor. These programmed tasks are absent in most engineering programs. The intent behind these tasks is to ensure that students have access to information vital to their selection, which also aligns with Eisenhardt (1989) who states that systems and tasks that share information across the agent and the principal are more likely to be present in behavior-based contracts. Conversely, selection processes in engineering programs are typically only constrained by a selection completion date. Activities to seek information are occasionally present but rarely enforced. Therefore, we can conclude that through a PAT lens, engineering processes can be classified as outcome-based, whereas math and science processes tend to be classified as behavior-based.

Our findings also show how funding distribution impacts faculty members' behavior regarding risk. In science and math programs, the presence of department funding for students via teaching assistantships allow programs to use this 'community fund' to minimize the risk of individual faculty members funding a student who may ultimately decide to work with a different colleague long-term. Science and math programs can fund students for longer periods of time out of this community fund, thereby minimizing the risk to individual faculty members by collectively sharing this financial risk across the department. Conversely, in engineering, the lack of such community funds forces faculty members to fund students with research assistantships earlier in the process. On the student side in engineering, students select an advisor sooner in the process than students in math and science programs, which puts them at risk of securing a tenuous advisor match, given that they have less time and activities to assess the fit of one (Devos et al., 2016). On the faculty side, individual faculty still risks funding a student who may not work with them long term. This behavior aligns with PAT, which states that risk minimization is more likely to be present in behavior-based contracts (Eisenhardt, 1989), which are practiced in science and math programs.

Given existing research, we find key insights into possible consequences when considering the impact of both an outcome or behavior-based process. Considering the reports of students appreciating the ability to select their advisor but feeling unsupported in doing so (Onen, 2016), it could be concluded that behavior-based contracts that do not limit the selection could help provide some of the desired support. Behavior-based processes could also help level the playing field for women and minoritized groups by helping students rely less on the informal networks that are often not available to them due to systemic inequities (Maher et al., 2020b; Posselt & Grodsky, 2017). These processes also help to provide more interaction opportunities between students and faculty prior to the selection, which is argued to reduce reliance on standardized test scores and grade-point averages as selection criteria (Miller et al., 2019; Posselt et al., 2019). Yet, one must not discount the possibility that a student's experiences in rotations and other similar experiences prior to formal selection may not reflect their actual advising experiences (Maher et al., 2020b). Ultimately, any advising relationship does have a trust element involved (Robertson, 2017).

Chemical engineering and matched advising relationships

The previously discussed findings do hold one exception, as chemical engineering programs in our sample are consistently at the crossroads between those observed for the sciences/math and engineering. The chemical engineering programs in our sample provide initial funding for students, so they undergo a selection process without pressure from faculty members to stay on any one project. Students typically have to engage in seminars and interviews, although the level of participation enforcement in such tasks varies across programs. Both behaviors align with the models observed for the sciences and math. However, these programs allow exceptions for faculty doing 'direct-hires' into their research group, as long as the faculty members are committed to fully funding such students from day one, a practice that we only observe in engineering programs. Uniquely, chemical engineering programs in our sample place the selection on the program director, as this person creates advisor–advisee matches based on students' preferences and resource availability. We have reported both the faculty and student perspectives within these programs elsewhere (de-identified for review).

Implications

Our findings present several implications for research. First, we show how different elements of the selection process vary across programs and suggest the possible impacts of each. While time to selection varies across fields and can relate to average time differences in degree completions, the lack of onboarding activities in certain processes may limit the information that both students and faculty obtain prior to finalizing a selection, which can ultimately lead to mismatches in advisor–advisee pairs. Future work should examine the actual impact of each of these selection elements from the perspectives of students and faculty. For example, future work could consider whether students selecting an advisor as part of their matriculation process, and thus becoming "locked in" to a dissertation topic (and funding source) early, has a long-term influence on their development and outcomes. Other research should directly assess whether onboarding activities and different information systems (e.g., engaging in onboarding and information systems' processes, ability to contribute meaningfully on research projects, time to degree) do induce changes in students' interests or thinking around potential advisors relative to their first matriculation. Such an analysis would determine how to optimize everyone's time, including the students', faculty's, and program directors', which has important financial implications. While some engineering education research has looked at this decision process (Mosyjowski et al., 2017), a key future direction could be the timing of this decision and its impact on both the advisor relationship and satisfaction with students' choice of research.

Our work also show how using theoretical frameworks from behavioral economics in doctoral education allow for interpretations through a non-traditional lens. Our findings demonstrate key differences in the doctoral experiences of students in engineering, math, and science. For this reason, future research should consider the implications of grouping STEM disciplines together in graduate education—and educational research more broadly—and the ways this grouping could impact their findings and conclusions. Using PAT helps us classify the processes and extract inherent properties that suggest possible ramifications of each process. While PAT can often simplify the complexities of real-life scenarios such as transient preferences and variable knowledge asymmetries (Shapiro, 2005), further research could leverage PAT and other similar theories for researching the policies or processes guiding the interactions between students and faculty and how these dynamics impact the advising relationship.

Our findings also show key implications for practice. Although it would be desirable to have a one-size-fits all solution for the conundrum of matching students to advisors, one needs to proceed with caution when recommending specific selection processes. Providing blanket recommendations without considering the contextual nuances and the individual experiences of students and faculty would be irresponsible, as there is no such thing as a perfect process (Artiles & Matusovich, 2022b). Even within a seemingly perfectly designed scenario, there can be areas of tension for students, faculty, and program leadership (Artiles & Matusovich, 2022b). Therefore, we recommend that graduate programs first assess their objectives in such a process, their contextual constraints, and their resource availability. We hope that our findings can help programs think through the different options that they may consider for each aspect of the advisor selection process and some of the different tradeoffs that appear to be associated with each decision.

Our findings regarding models of funding show how common funding allocations can tie into advising selection processes, which ultimately directly impact how and why students select advisors. When considering these funding models alongside the inevitable constraints that they place on timing to selection, we note that programs that employ a homogenous funding model have more structures in place post-matriculation so that students and faculty have the opportunities to explore their potential matches in greater detail. We see that exploration time as a positive feature, but recognize that programs differ in their access to a common funding source. Our analyses also did not consider the negative implications that may be associated with a later advisor selection, such as time to degree, which ultimately has an important resource consideration.

Our results highlight that programs that link together funding, admission, and advisor selection (i.e., the diversified funding model) may want to consider how information systems might be built into the recruitment and yield processes more formally so that students can still receive scaffolded support in making their decisions. We wonder if bringing such intentionality into students' decision-making processes about which graduate school to attend can ultimately help students and faculty alike make beneficial matches. Essentially, programs with diversified funding models may want to consider how results from other models could help strengthen their approach. For example, if programs that follow the diversified funding model approach still find themselves struggling with student–advisor conflicts and have tried changes to their recruitment and yield processes, our findings suggest that they may benefit from bringing together a common set of resources that enables some of the different timing practices outlined in our analyses.

We suggest that these connections, as discussed, can have a direct impact on the experiences of women and minoritized students in particular, which many science, engineering, and math programs are keen to recruit. Therefore, how institutions and programs choose to manage their funding can directly impact students' experience and possibly doctoral attrition and persistence.

Conclusion

This analysis provides three significant contributions to the existing research on doctoral education, specifically regarding the advisor selection process. The first contribution of this study is that it provides an analysis of the disciplinary norms and practices that exist within the fields of science, math, and engineering. This study shows where the disciplinary differentiation lies within science, math, and engineering and how practices are unique to each of these fields and the disciplines within them. The second contribution of this study is the expansion of the analytical generalizability of PAT in the space of student interactions within the practices of disciplines in higher education. Following Lane's (2012) recommendations on expanding the use of PAT in higher education, this study furthers such research by discussing the interactions within academic departments and presents how information and risk are distributed within a commonplace process in such contexts. Third, the study provides extended descriptions of the advisor selection processes currently in practice. By furthering the literature on doctoral education by exploring the process of advisor selection, this study presents a fuller picture of the formation of the relationship between the advisor and the advisee. This information could also be used to further understand doctoral attrition and foster the development of student support structures aiming to foment a positive advising relationship. We recommend that future research should evaluate individual faculty and student experiences in these processes, particularly how they may affect the development of the advising relationship and further experiences and outcomes of doctoral programs. We also recommend an in-depth look into how these processes compare for faculty and students who are assigned rather than self-selected.

Author contributions

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by the first and second authors. The first draft of the manuscript was written by first author and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Funding

This work is based on research supported by the National Science Foundation under Grant Nos. 1535226 & 1723314. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

Availability of data and materials

Data may be available upon request to the second author.

Code availability

Not applicable.

Declarations

Ethics approval and consent to participate

Approved by human subjects research at Virginia Tech.

Consent for publication

Approved by human subjects research at Virginia Tech.

Competing interests

The authors declare they have no financial interests.

Received: 27 January 2022 Accepted: 21 December 2022
Published online: 24 January 2023

References

Artiles, M. S., & Matusovich, H. M. (2022a). Choosing a doctoral advisor: A study of chemical engineering students' perspectives using basic needs theory. *International Journal of Engineering Education, 38*(5), 1212–1222.

Artiles, M. S., & Matusovich, H. M. (2022b). Doctoral advisor selection in chemical engineering: Evaluating two programs through principal-agent theory. *Studies in Engineering Education*. https://doi.org/10.21061/see.57

Bair, C. R., & Haworth, J. G. (2004). Doctoral student attrition and persistence: A meta-synthesis of research. In: *Higher education: Handbook of theory and research* (pp. 481–534). Springer, Dordrecht.

Barnard, R. A., & Shultz, G. V. (2020). "Most important is that they figure out how to solve the problem": How do advisors conceptualize and develop research autonomy in chemistry doctoral students? *Higher Education, 79*(6), 981–999. https://doi.org/10.1007/s10734-019-00451-y

Barnes, B. J., & Austin, A. E. (2009). The role of doctoral advisors: A look at advising from the advisor's perspective. *Innovative Higher Education, 33*(5), 297–315. https://doi.org/10.1007/s10755-008-9084-x

Becher, T., & Trowler, P. (1989). Academic tribes and territories Milton Keynes. *Society for Research into Higher Education*.

Biglan, A. (1973). The characteristics of subject matter in different academic areas. *Journal of Applied Psychology, 57*(3), 195.

Borrego, M., Choe, N. H., Nguyen, K., & Knight, D. B. (2021). STEM doctoral student agency regarding funding. *Studies in Higher Education, 46*(4), 737–749. https://doi.org/10.1080/03075079.2019.1650737

Burt, B., McKen, A., Burkhart, J., Hormell, J., & Knight, A. (2016, June 16). *Racial microaggressions within the advisor-advisee Relationship: Implications for engineering research, policy, and practice* [conference presentation]. 2016 ASEE Annual Conference & Exposition, New Orleans, Louisiana, United States. https://doi.org/10.18260/p.26029

Crede, E., & Borrego, M. (2012). Learning in graduate engineering research groups of various sizes. *Journal of Engineering Education, 101*(3), 565–589. https://doi.org/10.1002/j.2168-9830.2012.tb00062.x

Denis, C., Colet, N. R., & Lison, C. (2018). Doctoral supervision in North America: Perception and challenges of supervisor and supervisee. *Higher Education Studies, 9*(1), 30. https://doi.org/10.5539/hes.v9n1p30

Devos, C., Boudrenghien, G., Van der Linden, N., Frenay, M., Azzi, A., Galand, B., & Klein, O. (2016). Misfits between doctoral students and their supervisors: (How) are they regulated? *International Journal of Doctoral Studies, 11*, 467–486. https://doi.org/10.28945/3621

Dill, D. D., & Soo, M. (2004). Transparency and quality in higher education markets. In: *Markets in Higher Education* (pp. 61–85). Springer, Dordrecht.

Edwards, J. R., Caplan, R. D., & Van Harrison, R. (1998). Person-environment fit theory. *Theories of Organizational Stress, 28*(1), 67–94.

Eisenhardt, K. M. (1989). Agency theory: An assessment and review. *Academy of Management Review, 14*(1), 57–74.

Ferrer de Valero, Y. (2001). Departmental factors affecting time-to-degree and completion rates of doctoral students at One Land-Grant Research Institution. *The Journal of Higher Education, 72*(3), 341–367. https://doi.org/10.2307/2649335

Flora, B. H. (2007). Graduate assistants: Students or staff, policy or practice? The current legal employment status of graduate assistants. *Journal of Higher Education Policy and Management, 29*(3), 315–322. https://doi.org/10.1080/13600800701460867

Gardner, S. K. (2009). Conceptualizing success in doctoral education: Perspectives of faculty in seven disciplines. *The Review of Higher Education, 32*(3), 383–406. https://doi.org/10.1353/rhe.0.0075

Gardner, S. K. (2010). Contrasting the socialization experiences of doctoral students in high- and low-completing departments: A qualitative analysis of disciplinary contexts at One Institution. *The Journal of Higher Education, 81*(1), 61–81. https://doi.org/10.1353/jhe.0.0081

Golde, C. M. (2005). The role of the department and discipline in doctoral student attrition: Lessons from four departments. *The Journal of Higher Education, 76*(6), 669–700. https://doi.org/10.1080/00221546.2005.11772304
Golde, C. M., & Dore, T. M. (2001). *At cross purposes: What the experiences of today's doctoral students reveal about doctoral education*. Pew Charitable Trusts.
Goldman, C. A., & Massy, W. F. (2001). *The PhD factory: Training and employment of science and engineering doctorates in the United States*. Anker Publishing Company, Inc.
Grant, B. M. (2010). The limits of 'teaching and learning': Indigenous students and doctoral supervision. *Teaching in Higher Education, 15*(5), 505–517. https://doi.org/10.1080/13562517.2010.491903
Grote, D., Patrick, A., Lyles, C., Knight, D., Borrego, M., & Alsharif, A. (2021). STEM doctoral students' skill development: Does funding mechanism matter? *International Journal of STEM Education, 8*(1), 50. https://doi.org/10.1186/s40594-021-00308-w
Guillaume, N., Jones, S. M., De La Fosse, K., et al. (2020). Academic residency: Effective engagement and mentorship of doctoral students. *Journal of College Teaching & Learning (TLC), 17*(1), 1–10.
Hammond, T. H. (2005). Herding Cats in University Hierarchies: Formal Structure and Policy Choice in. *Governing Academia: Who is in Charge at the Modern University?, 91*.
Hayles, C. (2021). *Breaking down barriers: Using collaboration to increase the accessibility of campus resources for graduate students* [Master's Thesis, University of San Diego]. Digital USD. Retrieved from https://digital.sandiego.edu/soles-mahel-action/69
Heaton, J. (2004). *Reworking qualitative data*. Sage.
Hilmer, C. E., & Hilmer, M. J. (2007). On the relationship between the student-advisor match and early career research productivity for agricultural and resource economics Ph.Ds. *American Journal of Agricultural Economics, 89*(1), 162–175.
Hopwood, N., & McAlpine, L. (2007). Exploring a theoretical framework for understanding doctoral education. *Proceedings of the Annual Conference of the Higher Education Research and Development Society of Australia*, 1–8.
Joy, S., Fen Liang, X., Bilimoria, D., & Perry, S. (2015). Doctoral advisor-advisee pairing in STEM fields: Selection criteria and impact of faculty, student and departmental factors. *International Journal of Doctoral Studies, 10*, 343–363. https://doi.org/10.28945/2302
Kinoshita, T. J., Knight, D. B., Borrego, M., & Wall Bortz, W. E. (2020). Illuminating systematic differences in no job offers for STEM doctoral recipients. *PLoS ONE, 15*(4), e0231567. https://doi.org/10.1371/journal.pone.0231567
Knight, D., Kinoshita, T., Choe, N., & Borrego, M. (2018). Doctoral student funding portfolios across and within engineering, life sciences and physical sciences. *Studies in Graduate and Postdoctoral Education, 9*(1), 75–90. https://doi.org/10.1108/SGPE-D-17-00044
Kristof, A. L. (1996). Person-organization fit: An integrative review of its conceptualizations, measurement, and implications. *Personnel Psychology, 49*(1), 1–49.
Lane, J. E. (2012). Agency theory in higher education organizations. In M. N. Bastedo (Ed.), *The organization of higher education: Managing colleges for a new era* (pp. 278–303). Johns Hopkins University Press.
Lattuca, L. R., & Stark, J. S. (2009). *Shaping the college curriculum: Academic plans in context* (2nd ed.). Jossey-Bass.
Leech, N. L., & Onwuegbuzie, A. J. (2007). An array of qualitative data analysis tools: A call for data analysis triangulation. *School Psychology Quarterly, 22*(4), 557–584. https://doi.org/10.1037/1045-3830.22.4.557
Levecque, K., Anseel, F., De Beuckelaer, A., Van der Heyden, J., & Gisle, L. (2017). Work organization and mental health problems in PhD students. *Research Policy, 46*(4), 868–879. https://doi.org/10.1016/j.respol.2017.02.008
Lincoln, Y. S., & Guba, E. G. (1985). *Naturalistic inquiry*. Sage Publications.
Lozano, J., & Hughes, R. (2017). Representation and conflict of interest among students on higher education governing boards. *Journal of Higher Education Policy and Management, 39*(6), 607–624.
Maher, M. A., Wofford, A. M., Roksa, J., & Feldon, D. F. (2020a). Exploring early exits: Doctoral attrition in the biomedical sciences. *Journal of College Student Retention: Research, Theory & Practice, 22*(2), 205–226. https://doi.org/10.1177/1521025117736871
Maher, M. A., Wofford, A. M., Roksa, J., & Feldon, D. F. (2020b). Finding a fit: Biological science doctoral students' selection of a principal investigator and research laboratory. *CBE Life Sciences Education, 19*(3), ar31. https://doi.org/10.1187/cbe.19-05-0105
McAlpine, L., Castello, M., & Pyhaltö, K. (2020). What influences PhD graduate trajectories during the degree: A research-based policy agenda. *Higher Education, 80*(6), 1011–1043. https://doi.org/10.1007/s10734-019-00448-7
McCray, J., & Joseph-Richard, P. (2020). Towards a model of resilience protection: Factors influencing doctoral completion. *Higher Education, 80*(4), 679–699. https://doi.org/10.1007/s10734-020-00507-4
Miles, M. B., Huberman, A. M., & Saldaña, J. (2014). *Qualitative data analysis: A methods sourcebook* (3rd ed.). SAGE Publications, Inc.
Milkman, K. L., Akinola, M., & Chugh, D. (2012). Temporal distance and discrimination: An audit study in academia. *Psychological Science, 23*(7), 710–717. https://doi.org/10.1177/0956797611434539
Miller, C. W., Zwickl, B. M., Posselt, J. R., Silvestrini, R. T., & Hodapp, T. (2019). Typical physics Ph.D. admissions criteria limit access to underrepresented groups but fail to predict doctoral completion. *Science Advances, 5*(1), 7550. https://doi.org/10.1126/sciadv.aat755
Moreira, R. G., Butler-Purry, K., Carter-Sowell, A., Walton, S., Juranek, I. V., Challoo, L., Regisford, G., Coffin, R., & Spaulding, A. (2019). Innovative professional development and community building activity program improves STEM URM graduate student experiences. *International Journal of STEM Education, 6*(1), 34. https://doi.org/10.1186/s40594-019-0188-x
Mosyjowski, E. A., Daly, S. R., & Peters, D. L. (2017). Drivers of research topic selection for engineering doctoral students. *International Journal of Engineering Education, 33*(4), 1283–1296.
Muller, J. (2009). Forms of knowledge and curriculum coherence. *Journal of Education and Work, 22*(3), 205–226.
Nettles, M. T., & Millett, C. M. (2006). *Three magic letters: Getting to Ph.D.* Johns Hopkins University Press.
Noy, S., & Ray, R. (2012). Graduate students' perceptions of their advisors: Is there systematic disadvantage in mentorship? *The Journal of Higher Education, 83*(6), 876–914. https://doi.org/10.1080/00221546.2012.11777273
Onen, D. (2016). Factors influencing student choice of the research supervisor: A study of doctoral students. In Dichaba M. M. & Sotayo, M. A. O. (Eds.), *Towards excellence in educational practices* (pp. 27–39). South Africa International Conference on Education.
Polmear, M., & Simmons, D. (2020). Developing and sustaining a research group: A novel approach to onboarding doctoral students. *ASEE Virtual Annual Conference Content Access Proceedings*. https://doi.org/10.18260/1-2-34425
Posselt, J. R. (2015). Disciplinary logics in doctoral admissions: Understanding patterns of faculty evaluation. *The Journal of Higher Education, 86*(6), 807–833. https://doi.org/10.1353/jhe.2015.0030
Posselt, J. R., & Grodsky, E. (2017). Graduate education and social stratification. *Annual Review of Sociology, 43*(1), 353–378. https://doi.org/10.1146/annurev-soc-081715-074324
Posselt, J. R., Hernandez, T. E., Cochran, G. L., & Miller, C. W. (2019). Metrics first, diversity later? Making the short list and getting admitted to Physics PhD programs. *Journal of Women and Minorities in Science and Engineering, 25*(4), 283–306. https://doi.org/10.1615/JWomenMinorScienEng.2019027863
Posselt, J. R., Porter, K. B., & Kamimura, A. (2018). Organizational pathways toward gender equity in doctoral education: Chemistry and civil engineering compared. *American Journal of Education, 124*(4), 383–410.
Robertson, M. J. (2017). Trust: The power that binds in team supervision of doctoral students. *Higher Education Research & Development, 36*(7), 1463–1475. https://doi.org/10.1080/07294360.2017.1325853
Rudolph, A. L., Holley-Bockelmann, K., & Posselt, J. R. (2019). PhD bridge programmes as engines for access, diversity and inclusion. *Nature Astronomy, 3*(12), 1080–1085. https://doi.org/10.1038/s41550-019-0962-1
Scherr, R. E., Plisch, M., Gray, K. E., Potvin, G., & Hodapp, T. (2017). Fixed and growth mindsets in physics graduate admissions. *Physical Review Physics Education Research, 13*(2), 020133. https://doi.org/10.1103/PhysRevPhysEducRes.13.020133
Schlosser, L. Z., & Gelso, C. J. (2001). Measuring the working alliance in advisor-advisee relationships in graduate school. *Journal of Counseling Psychology, 48*(2), 157–167. https://doi.org/10.1037/0022-0167.48.2.157
Schlosser, L. Z., Knox, S., Moskovitz, A. R., & Hill, C. E. (2003). A qualitative examination of graduate advising relationships: The advisee perspective. *Journal of Counseling Psychology*. https://doi.org/10.1177/0011000006290249

Shapiro, S. P. (2005). Agency theory. *Annual Review of Sociology, 31*(1), 263–284. https://doi.org/10.1146/annurev.soc.31.041304.122159
Shulman, L. S. (2001). *The Carnegie classification of institutions of higher education*. Carnegie Publication.
Slay, K. E., Reyes, K. A., & Posselt, J. R. (2019). Bait and switch: Representation, climate, and tensions of diversity work in graduate education. *The Review of Higher Education, 42*(5), 255–286. https://doi.org/10.1353/rhe.2019.0052
Sowell, R., Allum, J., & Okahana, H. (2015). *Doctoral initiative on minority attrition and completion*. Council of Graduate Schools.
Sowell, R., Zhang, T., Bell, N., Redd, K., & King, M. F. (2008). *PhD completion and attrition: Analysis of baseline data*. Council of Graduate Schools.
Thaler, R. H., & Sunstein, C. R. (2008). *Nudge: Improving decisions about health, wealth, and happiness*. Yale University Press.
Torka, M. (2018). Projectification of doctoral training? How research fields respond to a new funding regime. *Minerva, 56*(1), 59–83. https://doi.org/10.1007/s11024-018-9342-8
Tracy, S. J. (2010). Qualitative quality: Eight "big-ten" criteria for excellent qualitative research. *Qualitative Inquiry, 16*(10), 837–851. https://doi.org/10.1177/1077800410383121
Weeden, K., Thébaud, S., & Gelbgiser, D. (2017). Degrees of difference: Gender segregation of US doctorates by field and program prestige. *Sociological Science, 4*, 123–150. https://doi.org/10.15195/v4.a6
Weiner, B. (1985). An attributional theory of achievement motivation and emotion. *Psychological Review, 92*(4), 548–573. https://doi.org/10.1037/0033-295X.92.4.548
Zhao, C.-M., Golde, C. M., & McCormick, A. C. (2007). More than a signature: How advisor choice and advisor behaviour affect doctoral student satisfaction. *Journal of Further and Higher Education, 31*(3), 263–281. https://doi.org/10.1080/03098770701424983

Publisher's Note