Contemporary Mathematics and Science Education
2024, 5(2), ep24013
ISSN 2634-4076 (Online)
https://www.conmaths.com/
Review Article
OPEN ACCESS

An interdisciplinary approach to studying academic success in STEM

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Citation: Taasoobshirazi, G., Peifer, J., Duncan, L., Ajuebor, A., & Sneha, S. (2024). An interdisciplinary approach to studying academic success in STEM. *Contemporary Mathematics and Science Education*, 5(2), ep24013. https://doi.org/10.30935/conmaths/14791

ABSTRACT

This paper recommends that the research on giftedness, expertise, and gender/racial disparities in science be used in combination, on behalf of a new theoretical framework, for studying academic success in science, technology, engineering, and mathematics. The variables characterizing expertise are presented followed by a discussion of what constitutes giftedness. We then discuss the variables considered to be contributing factors to gender and racial disparities in science. The paper concludes that the variables that define these areas of research can comprehensively identify and provide a firm paradigm for what researchers should evaluate collectively to understand success in science. We put forth several recommendations for future research studying science learning and for efforts to support expertise, particularly for women and underrepresented minorities.

Keywords: expertise, gender differences, giftedness, racial disparities, science education

Received: 07 Mar. 2024 ◆ Accepted: 13 May 2024

INTRODUCTION

In the early 2000s, Judith Ramaley of the National Science Foundation (NSF) has been credited with wide operationalization and dissemination of the acronym STEM (science, technology, engineering, and mathematics) to refer to a varied collection of disciplines and careers of specific interest to a range of US national policy concerns and goals (Fortenberry, 2000). Previously, this national, strategic focus on STEM underscored the direct role that those in these fields play in driving economic growth (Yamada, 2023), environmental sustainability (Hwang et al., 2023), technological advances (Oladele et al., 2023), and national health (Kaya-Capocci & Ucar, 2023), as well as individual and societal prosperity and welfare (Kaya-Capocci & Ucar, 2023). The demand for graduates with STEM degrees in today's technologically advanced, fast-paced, and highly connected world continues to increase (Redden, 2020). However, the USA faces a shortage of graduates with science, technology, engineering, and mathematics degrees needed to fill the related, imminent professions (Peterson, 2024). Moreover, the USA is no longer "the uncontested leader in science and engineering" with global talent and education blossoming in these areas (Redden, 2020).

In this context, the USA cannot afford to continue to sideline large swaths of their potential workforce with women, Latine, Black, American Indian, and Pacific Islanders STEM workers representation rates mismatched to their national presence (NSF, 2021). Despite strides between 2011 and 2021 demonstrating increased representation, the COVID-19 pandemic heightened this marginalization, spurring a disproportionate number of women–particularly minorities–to leave the professional workforce (Ellingrud & Segel, 2021). Indeed, early research on the social effects of the pandemic shows that the pandemic and its economic repercussions has hit early-career women scientists particularly hard as more women than men are forced to work from home and away from their labs while managing family and childcare obligations (Esquivel et al., 2023; Lawson et al., 2023). A comprehensive and inclusive science education is key to producing qualified talent that is, now post-pandemic, needed more than ever to fill science and engineering occupations.

The primary goal of science education is to develop students' expertise. Carl Wieman, recipient of the Nobel Prize in physics, explains this goal in the following way:

> "Expert competence is a primary goal of education and is an area in which research has provided useful insights. An apt metaphor is that of the student and the expert separated by the mental equivalent of a canyon; the function of teaching is to guide the student along the path that leads safely and effectively across the canyon to the nirvana of expert-like thinking" (Wieman & Perkins, 2005, p. 38-40).

In many ways, "gifted" education serves as one of the first entry points to a pipeline to later advanced courses, undergraduate and postgraduate education, and eventual STEM careers. Thus, understanding expertise development and giftedness enables us to

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create early pathways into these careers. In this paper we explore the intersection of research on what makes an expert and perseverance and success in STEM and gifted education, with a focus on the variables that contribute to disparities and gender and racial underrepresentation in the STEM field.

METHODOLOGY

We used several academic search engines, such as Web of Science and Scopus, to search for research on expertise, expertise in STEM, giftedness, giftedness in STEM, and gender and racial group differences in STEM. This led to hundreds of relevant peer-reviewed empirical and theoretical research articles. We reviewed the studies not to provide an extensive review here, but rather to identify and present the variables implicated as being linked to STEM success in these areas of research. These three areas of scholarship (expertise, giftedness, and historically marginalized groups in STEM), with some overlapping variables, can provide a firm and comprehensive framework for conducting research to understand and support student success in STEM.

EXPERTISE IN STEM

Expertise is most often described as a collection of characteristics that distinguishes experts from novices. Within their domain of practice, experts engage in more deliberate practice (Ericsson, 2006; van de Weil & Van den Bossche, 2013), use better strategies when solving problems (Alexander, 2003), have greater and more organized conceptual knowledge (Hatano & Oura, 2003), have greater motivation to engage in deliberate practice (Alexander, 2003), and are more metacognitive (Zimmerman, 2006). While these are defining characteristics of experts across most domains, there are defining characteristics that are domain specific. For example, in computer science, expert programmers run code in a more linear and concise fashion (Emhardt et al., 2018). In medicine, the development of expertise is tied to the formation of illness scripts that are then used to diagnose new cases (Schmidt & Rikers, 2007). The empirical research on expertise in STEM focuses primarily on cognitive factors such as strategy use, physical representations (such as free-body diagrams in physics), and conceptual knowledge; most of this research is cross-sectional, in physics, and compares novices (college-level physics students) and experts (practicing physicists). There is limited assessment of the development of expertise or the larger social context in which expertise emerges.

GIFTEDNESS IN STEM

The concept of giftedness continues to evolve. In addition to high scores on standardized tests, there are numerous cognitive, creative, affective, and behavioural variables that characterize giftedness in general across all domains. The recognition of these characteristics, by parents and teachers, in students, has been one method of identifying and placing them in gifted science classes and programs. Most of these variables are considered conceptual definitions of giftedness and are broad (Paul & Moon, 2016). Examples include that gifted students are more creative, are keen observers, have advanced empathy, ask many intelligent questions, are highly curious, have a tendency for fantasy, are voracious readers, prefer the company of adults, and have a keen sense of humour (Sternberg, 2024).

Sternberg (2024) highlighted the three-way interaction connecting the individual, task, and situation that results in labelling of excellence on a societally revered task. This underscores the complex exchange between social valuation, performance, and the concept of unique skilledness. Research on giftedness notes the role of how social contexts influence the emergence of giftedness and the role caregivers, teachers, and peers play in supporting or suppressing the expression of these skills (Abuhamdeh & Csikszentamihalyi, 2004). In STEM, gender and racial biases may inhibit the identification of women and many members of minoritized groups as “gifted” in fields that have been historically dominated by cis-gender, White men (Sternberg, 2023).

Much of the work on giftedness focuses in on the assessment and evaluation of it (Dai, 2020; Milic & Simeunovic, 2020), what makes an individual gifted (Dai, 2020; Turkman, 2020), and for how long someone is defined as gifted (Ford, 2021; Sternberg et al., 2021). Some researchers posit that early giftedness is simply expertise in development (Sternberg, 2003; Subotnik & Jarvin, 2005) In fact, Sternberg (2003) argues that one cannot differentiate between giftedness and expertise simply because all measures of giftedness assess some form of expertise. IQ and other standardized tests have remained a standard method of assessing and placing students in gifted program pipelines and STEM programs, but the efficacy of their use in identifying students has been debated due to concerns about racial, gender, socioeconomic, and linguistic bias present in most widely used measures (Sternberg, 2017).

Some of the domain specific operational definitions for giftedness overlap with the variables reported in the work on expertise in STEM. For example, students identified for gifted programs are more metacognitive (Neber & Schommer-Aikins, 2002), more motivated (Mammadov et al., 2018), have more knowledge that is well organized (Kim & Choi, 2012), and use better problem-solving strategies (Kim & Choi, 2012). Other operational definitions include that gifted students receive greater parent and teacher support (Wellisch, 2021), tend to be perfectionists (Esparza et al., 2014), show more buoyancy (Winner, 1996), have better spatial skills (Yoon & Mann, 2017), and are more open to the ambiguous (Merrotsy, 2013).

A gifted student may also engage in the deliberate practice that leads to expertise or they may lose the motivation or support necessary to transition from giftedness to expertise. Gifted students must continue to practice and improve the skills that make and keep them gifted or they will stop being identified as gifted (McBee et al., 2018). In other words, gifted adults are considered experts. Failure of gifted students to transition to expertise and reach their full potential prevents them from making substantial contributions to society, which can be a loss for humanity at large.

RACIAL & GENDER GAPS IN STEM FIELDS

The low inclusion of women, Latine, Black, American Indian, and Pacific Islanders in advanced science degrees in the USA, particularly in STEM degrees, is a contributing factor to the obstacle in filling the associated workforce demand and responding to the high need for necessary talent (NSF, 2021). Underrepresented minority women in the USA are especially disadvantaged (NSF, 2021).

Researchers have identified several explanations for these gender and racial disparities, including teacher and parental support (Grossman & Porche, 2014), motivation (Enman & Lupart, 2000), enrollment patterns (Vooren et al., 2022), hands-on experience (Desouza & Czemiak, 2002), and stereotype threat (Grossman & Porche, 2014; Marchand & Taasoobshirazi, 2013).

The research on gender and minority group differences in STEM neglects the cognitive and metacognitive variables that are studied extensively in the research on giftedness (Chi et al., 2014). However, the research on gender and minority group differences in science, like the research in giftedness, does consider teacher and familial support (both of which are neglected in the expertise research). The gender and racial disparities research in STEM also brings in the unique evaluation of hands-on experience during authentic play (Desouza & Czemiak, 2002). This is valuable because the research on expertise does not compare novices and experts on novel, open-ended, and complex tasks that those in STEM must learn to engage in effectively. Instead, experts and novices are usually compared on their ability to solve basic science problems (Chi et al., 2014). The research on gender, race and giftedness sometimes takes a developmental and longitudinal perspective; the work on expertise is primarily cross-sectional in nature. The research on giftedness considers unique variables such as spatial skills, perfectionism, and buoyancy, none of which are considered in the expertise literature. Only spatial skills have been studied, to a small extent, in the research on gender and racial disparities in science as a contributing factor to the low performance of women and underrepresented groups in science. In fact, the only variable common across all three areas of research is motivation (Bal-Tastan et al., 2018).

GAPS IN CURRENT RESEARCH & RECOMMENDATIONS FOR NEW RESEARCH

Some research has identified the variables linked to expertise in STEM fields (Alexander, 2003; Ericsson, 2006; van de Weil & Van den Bossche, 2013), but more work can help elucidate the connections between giftedness and expertise cultivation in the STEM field, particularly for underrepresented populations. Variables in the expertise research tend to be studied independently. There is a lack of research examining the relationships among these variables across these three areas of research and little understanding of which variables are most essential for success in STEM and at what time and for what groups of individuals.

As a result, teachers and researchers do not know what should be focused on during STEM instruction and what is of less importance. The available research (such as Wieman & Perkins, 2005) provides little direction on the best way to move students towards more expert levels of performance. Understanding what is and what is not important for transitioning students towards expert performance is an important precursor for modifying instruction. The same issues are also present in the research on giftedness. First, the operational variables that define giftedness tend to be studied individually in empirical research. Furthermore, there is a gap between the research on giftedness in children and expertise in adults. The work on giftedness could enhance the work on expertise so that giftedness is studied as emerging expertise. The road from giftedness to expertise is caused by multiple, interacting variables that should be studied together and comprehensively. Ideally, the characteristics we want to support in science classrooms are those linked to giftedness and expertise.

We lack information about how the variables described in the research on gender and racial differences in science, the variables in the gifted literature, and those described in the expertise research in STEM interact when studied together. Advanced modeling techniques, for example, can help us understand the interactions among these variables across these three areas of research. For example, structural equation modeling, multilevel modeling, and Hayes' conditional process modeling can allow for thorough tests of the interactions among these variables. These modeling techniques can identify longitudinal, nested, mediating, moderating, mediated moderation, and moderated mediation effects. This is important for a comprehensive understanding of how various cognitive, motivational, affective, contextual, and social variables interact. Qualitative interviews with small groups of gifted students and experts at varying levels of expertise and across various demographics can provide insight from the findings from statistical modeling.

The expertise research provides us with a snapshot of experts and novices in a problem-solving situation. What we do not understand is how these experts progressed towards expert performance. A developmental perspective using the research on giftedness, expertise, and gender/racial differences in STEM can provide an understanding of how experts are created, and how variables such as motivation, deliberate practice, and social support influence the transition to expertise. We know little about the early precursors to later developing scientific expertise and the gifted research can play a critical role here. Such a line of research would provide insight into how the path to expertise can be negatively influenced as is often the case for females and minorities, and how expertise can be better supported. A developmental perspective would also allow us to determine which variables are most important and at what time.

Finally, there is limited investigation of how STEM experts in function in the real world and on authentic tasks and problems (Ericsson, 2006) because the problems used to study experts in science, and compare them to novices, are basic textbook problems. The gifted research is only a little better about studying gifted students on authentic tasks and problems. By focusing on differences in basic problem-solving skills or test scores on standardized tests, research has missed key characteristics that are important in differentiating how experts and gifted students differ from novices and the non-gifted.

CONCLUSIONS

Studying the interactions among multiple, interdisciplinary variables can provide a comprehensive picture of what is important for success in STEM and at what time. It may be that deliberate practice is less important than strategy use early on, and that this relationship reverses as students continue their academic training. This information will allow educators to intervene accordingly to maximize learning, motivation, and participation, particularly for women and underrepresented minorities. Thus, this research will have important implications for intervention studies. As an example, the impact of imposter phenomenon on women's performance and participation in business, industry, and academia is becoming widely discussed (Parkman, 2016).

Studying imposter phenomenon among students and scientists, using the framework we presented, can provide insight into when imposter phenomenon develops and the variables that mediate and moderate imposter phenomenon. This will provide valuable information about what factors attenuate or exasperate imposter phenomenon and appropriate interventions can then be applied accordingly. As researchers expansively study the interaction among the many different variables in these three areas of research: *gender/racial differences in STEM, expertise in STEM,* and *giftedness in STEM*, it will become apparent if the instruments that are available are doing a proper job in assessment. Valid and reliable instruments are necessary, and this may lead to additional publications of instrument development and validation. Finally, to conclude, we quote Hambrick et al. (2014, p. 2):

> "For researchers interested in advancing the science of expert performance, the task now is to develop and rigorously test theories that take into account as many potentially relevant explanatory constructs as possible."

We encourage just that.

Author contributions: GT: conceptualization & writing & **JP, LD, AA, & SS:** writing. All other author contributed to the writing of the paper. All authors approved the final version of the article.

Funding: The authors received no financial support for the research and/or authorship of this article.

Ethics declaration: The authors declared that the study does not require approval from an ethics committee. The article presents a review of three areas of research and no participants were involved.

Declaration of interest: The authors declare no competing interest.

Data availability: Data generated or analyzed during this study are available from the authors on request.

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