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Elementary Science Teacher Candidates' Noticing and Interpretation of Student Sensemaking in the Context of Classroom-Level Phenomenon-Based Assessments

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ABSTRACT

This study examined elementary science teacher candidates' (TCs') ability to notice and interpret students' sensemaking and science ideas by analyzing written responses to classroom-based assessments implemented at the end of mini-units during their field placements. TCs were enrolled in a 16-week science methods course at a Midwestern university committed to preparing teachers for three-dimensional instruction, as outlined in the Framework for K–12 Science Education (National Research Council, 2012). As part of this broader focus on three-dimensional instruction, TCs also engaged in learning opportunities to design and implement classroom-based assessments grounded in real-world phenomena. These assessments varied in how strongly they were anchored in phenomena, providing a range of contexts for evaluating student thinking. After enacting their assessments, TCs collected and analyzed students' written responses to identify and interpret instances of sensemaking—defined as the process through which students figure out how or why something happens by articulating ideas, using evidence, and reasoning through science concepts (Odden & Russ, 2019). Using Kang and Anderson's (2015) framework of teacher noticing and responding, we examined how TCs made sense of student thinking. Findings indicate a clear connection between assessment design and noticing when assessments more effectively leveraged phenomena to elicit reasoning, TCs were more attuned to identifying and interpreting student sensemaking. This study underscores the importance of integrating assessment design with the teaching of three-dimensional instruction in teacher preparation programs.

Keywords: Sensemaking, Elementary Science, Teacher Education, Assessment.

Introduction

Background

Sensemaking is central to science classrooms, especially within the three-dimensional instructional framework promoted by the Next Generation Science Standards (NGSS) (Campbell, 2018; Johnson & Cotterman, 2015; Luna & Sherin, 2017; National Research Council [NRC], 2012; Sherin & van Es, 2005). This approach frames sensemaking as an active process where students construct or revise explanations to understand natural and designed phenomena (Odden & Russ, 2019; Penuel & Bell, 2016; Reiser, 2013;). Here, a science phenomenon is defined as an observable event that invites student investigation and explanation, focusing on uncovering the "how" and "why" behind it. The NGSS three-dimensional approach emphasizes sensemaking by involving students in science and engineering practices, as well as cross-cutting concepts, allowing them to explore phenomena in depth and develop a nuanced understanding of scientific ideas.

Research supports the role of phenomena in fostering three-dimensional instruction and aiding student sensemaking (Brown & Bybee, 2023; Lee & Grapin, 2022; Pellegrino et al., 2014; Schwarz et al., 2017; Zembal-Saul & Hershberger, 2019). Teacher practices of noticing and responding play a crucial role in this process, as teachers recognize, interpret, and build upon students' ideas to guide them in investigating and explaining phenomena more deeply (Berland & Reiser, 2009; Davis et al., 2017; Furtak & Ruiz-Primo, 2008; Gotwals & Birmingham, 2016; Hanuscin & Zangori, 2016; Kang & Anderson, 2015). Studies suggest that effective teacher noticing and responding help students meaningfully engage with the natural world, encouraging scientific reasoning and causal explanations (Hammer & Van Zee, 2006; Hutchison & Hammer, 2010; Luna, 2018; Russ et al., 2009).

Emerging research also explores teacher noticing within assessments, showing that high-quality assessments, which include open-ended questions inviting reasoning and evidence, engage teachers in productive noticing of students' ideas, thus supporting student sensemaking (Campbell, 2018; Furtak et al., 2016, 2020; Kang et al., 2014). Such assessments, when tied to phenomena, provide insights into students' understanding of events' underlying mechanisms, offering a richer context for applying concepts (Windschitl et al., 2012). In this study, we examine the role of phenomena as a core element in classroom-based assessments and its impact on elementary science teachers' noticing and responses to students' disciplinary thinking.

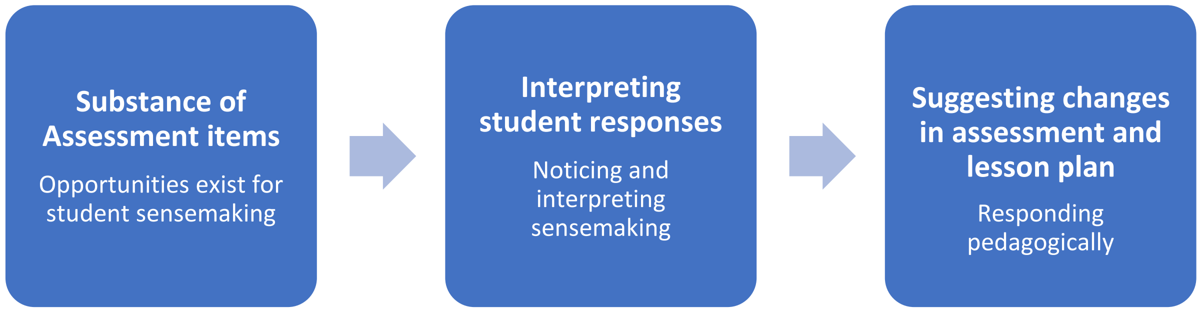
- What do elementary science teacher candidates (TCs) notice in students' written responses to phenomenon-based assessments, and how do they interpret these noticings as evidence of students' sensemaking and respond to them?
- How do TCs noticing and interpretation relate to the role of phenomena in assessments?
- What kinds of adaptations or improvements did TCs suggest for their assessment items based on their noticing and interpretation of students' responses?

Conceptual Framework for Analyzing TCs' Assessment Items and their Noticing and Interpretation of Students' Ideas

Classroom-based assessments were analyzed from 23 TCs and their analysis of students' written responses to these assessments when implemented in their classrooms. Building on the framework developed by Kang and Anderson (2015), a process was structured to investigate TCs' abilities to notice and interpret students' ideas through an analysis of student responses to assessments See Figure 1 for this information.

Figure 1

Responsiveness Toward Student Sensemaking Through Phenomenon-Based Assessments



This process followed three key steps:

1. Examining Opportunities for Sensemaking: We assessed whether and how the assessments provided by TCs allowed for student sensemaking. This involved identifying if the assessment tasks were centered around specific phenomena and gauging the extent to which they encouraged students to engage meaningfully with the content.
2. Connecting Candidates' Noticing and Interpretation: We analyzed the connections between what TCs noticed in students' responses and how they interpreted those responses in terms of students' understanding. This step aimed to reveal patterns in TCs' ability to recognize and interpret evidence of student sensemaking in response to assessment tasks.
3. Modifications to Enhance Assessments: We reviewed any modifications that TCs proposed to improve the assessments, particularly focusing on whether these adjustments aimed to enhance student sensemaking. Additionally, we explored how these adjustments were aligned with the goal of fostering deeper student understanding of the content.

Our analysis began by determining whether the assessment item chosen by each candidate was designed around a specific phenomenon, examining how it enabled students to make connections and construct meaning. TCs provided a written analysis detailing their observations, documenting instances of student sensemaking, and offering interpretations of those instances (see Annexure1). This systematic approach allowed us to identify recurring patterns in the ways TCs noticed, interpreted, and responded to student sensemaking within the context of phenomenon-based assessment items.

Study Context, Participants, and Learning Opportunities for TCs in Understanding Phenomenon-Based Assessments

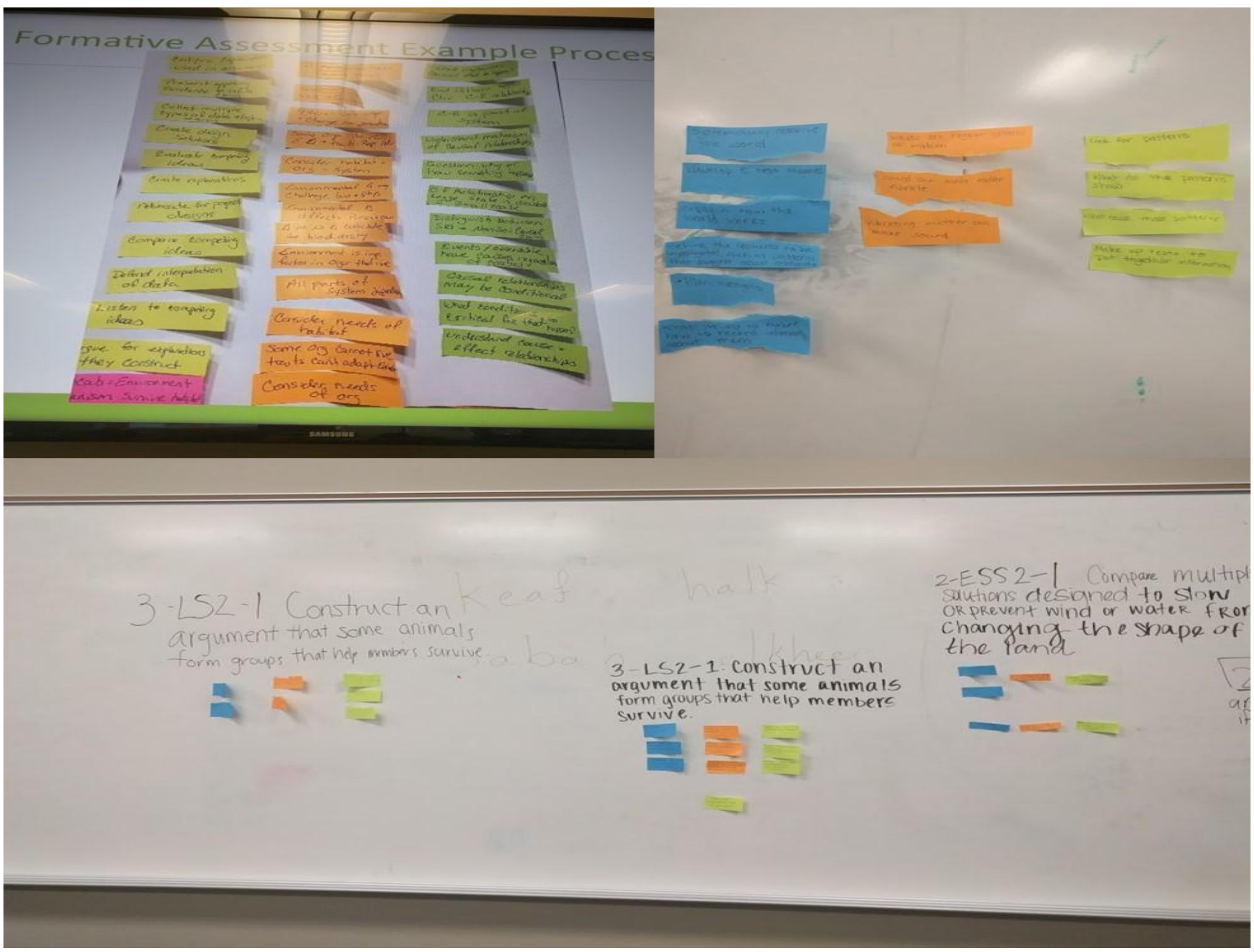
All 23 TCs in this study were enrolled in an NGSS-aligned elementary science methods course, which serves as the first pedagogy-based course in their teacher preparation program at a Midwestern university. This course is taken in the fall semester and is followed by a second methods course in the spring. Toward the end of the fall semester, TCs designed and taught two-day science lessons in their assigned elementary school field placement classrooms. As part of these lessons, they also developed and implemented classroom-level assessment items grounded in scientific phenomena.

As part of their coursework, TCs were provided learning opportunities to learn and develop their understanding of three-dimensional learning instruction (NRC, 2012) and examined the significance of grounding science instruction in real-life phenomena relevant to K–5 learners' everyday experiences. TCs had opportunities to read about and view examples of using phenomena as a way to elicit a wide range of student ideas. As the course progressed, to help candidates view an alignment between instruction and assessment, opportunities were introduced to help them learn about three dimensional assessments. One goal was to support candidates in designing assessments grounded in phenomena for their two-days science units—helping them shift from traditional, closed-ended assessments, to more open-ended tasks that could elicit students' reasoning and evidence-based thinking about the phenomenon .TCs also engaged in discussions about student sensemaking—what it looks like in practice—reinforcing the importance of affording students' use of evidence, reasoning, and explanations as they try to make sense of a phenomenon and respond to the assessment task they implemented.

All TCs participated in a three-hour workshop focused on unpacking the NGSS performance expectations into their three dimensions: disciplinary core ideas (DCIs), scientific practices (SPs), and crosscutting concepts (CCCs). This information is available in Figure 2.

Figure 2

Opportunities to Deepen Understanding of Phenomenon-Based Assessment While Unpacking the Three Dimensions of the NGSS



This workshop provided a foundation for designing phenomenon based, NGSS-aligned, three-dimensional assessment items. During the assessment workshop, candidates collaborated in small groups with peers, using performance expectations and examining them through the lens of all three NGSS dimensions. Throughout this process, TCs received ongoing input and guidance from course instructors and workshop leaders.

To design their assessment item(s) to be implemented at the ends of their two-day mini unit in their field placement classrooms, TCs identified relevant grade level appropriate NGSS performance expectations. Although the science methods course encouraged and guided TCs to create phenomenon-based assessments, mentors and curricula in their school placements may not have consistently supported this goal, resulting in variability in the guidance and modeling they received.

Data Sources and Analysis

Two primary sources of data were analyzed:

a) The first source of data was the design of 23 assessment items created and implemented by TCs at the end of their two-day instructional units.

b) The second source of data comprised TCs' analyses of their students' responses to the designed assessment items. Each teacher candidate selected six written work samples from their students, representing a range of responses. These submissions included both the student responses and the teacher candidate's written analysis. The analysis focused on identifying evidence of student sensemaking, with TCs offering their noticing and interpretations based on the analytic prompts provided in the course assignment (see Annexure 2).

Coding of Assessment Items

To conduct a comprehensive examination aligned with the responsiveness framework developed by Kang and Anderson (2015), we first analyzed the assessment items designed and implemented by each of the 23 TCs. The assessment task submitted by TCs as part of their course assignments offered valuable initial insight into their potential to support student sensemaking when implemented. Our coding of the assessment tasks was guided by the notion of how the assessment allowed for, or limited, opportunities for students to make sense of phenomena through their response.

In addition to designing, TCs also implemented their assessment items and collected student work samples for analysis. TCs examined whether and how student responses showed evidence of sensemaking of the science ideas underlying the phenomenon. Each teacher candidate selected six student work samples that reflected a range of responses to their assessment tasks. TCs analyzed these responses using course-provided prompts (see Annexure), considering what the students' ideas revealed, how the assessment supported or constrained sensemaking, and how students' thinking was made visible through their responses.

TCs' written reflections served as a valuable source of data for understanding how phenomenon-based assessments mediated what and how TCs noticed in students' ideas and interpreted them as evidence of sensemaking. The reflections also highlighted how the design features of the assessment tasks influenced their ability to notice and interpret student thinking. This dual analysis—of the phenomenon-based assessment tasks and TCs' reflections on student work—offered a comprehensive perspective on how assessments can be used to support responsive instruction in science classrooms.

We conducted coding of the assessment items, guided by the following questions, to explore the substance of the assessments designed by TCs. We used the following guiding questions: a) Was the phenomenon clearly defined to guide the assessment? In other words, did the assessment center around a natural process, or event, that students were expected to make sense of and explain?, b) If so, in what ways did the assessment give students a chance to build explanations about why and how the phenomenon happens? Did students have opportunities to notice important factors and patterns that affect the phenomenon, and use these ideas to explain what they observed? How were students encouraged to share their thinking and reasoning, as much as possible, in ways that make sense for their K-5 grade level?

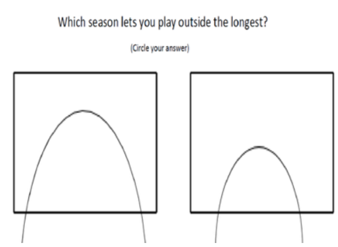
For clarity, TCs had limited time to implement an assessment at the end of their two-day lesson. Therefore, we did not explicitly delve into the extent to which an assessment item incorporated scientific practices or crosscutting concepts. Adapting from Kang and Anderson's (2015) definitions, we categorized the assessment tasks into the following groups.

1) Unproductive assessments characterized items that lacked a phenomenon, simply requiring students to present canonical information, check off boxes, or circle correct answers, without providing opportunities for student sensemaking or expressing their understanding of science.
2) Unproductive assessments with a phenomenon characterized items that included a phenomenon but did not engage students in sensemaking of the phenomenon, as they remained limited to closed-ended questions.
3) Phenomenon-based productive assessments, which effectively prompted students to engage in reasoning, data collection, interpretation, and the construction of scientific explanations.

See Table 1 for more information about the assessment types, characteristics, and examples.

Table 1

Descriptions and Examples of Assessment Types

Assessment Type	**Characteristics**	**Examples**
Unproductive assessment	No phenomenon is present in the assessment. The task focuses primarily on the reproduction and recall of fact-based information, emphasizing classification and description rather than engaging students in deeper sensemaking or application of concepts	How can you describe two new solids based on the knowledge of the properties used to describe solids in previous lessons?
	Although the phenomenon is present, it is not effectively utilized to promote student sensemaking or provide opportunities for students to demonstrate their understanding. Instead, the focus is primarily on the reproduction and recall of factual information, with an emphasis on classification and description, rather than encouraging deeper engagement with the phenomenon through analysis or explanation	

Assessment Type	Characteristics	Examples
		 Color in the picture that will offer you and your family the best protection from the sun and heat from the sun. Draw a structure that will offer protection to the dog below. Make sure that you include all of the essential components to your structure. **PHENOMENON**: *Sunlight and its effects*
Productive assessment	The assessment was designed around a real-world phenomenon, providing students with varying level of opportunities for meaningful sensemaking. It included questions that encouraged deeper reasoning and required students to explain their thinking, promoting a more comprehensive understanding of the concept.	Students will draw what they observed on the playground outside in the morning and in the afternoon and color their drawing based on how they think the object felt related to the temperature of the object: Blue=cold, Green=cool, Orange=warm, Red=hot. Also, the students will indicate where they found the object by either coloring the ground gray if they found the object in the shade, drawing a sun if they found the object in the sun, or explaining where they found the object in words, when asked individually. Thus, I will assess the students formatively by observing students as they conduct investigations to determine how sunlight affects the temperature of the objects that they touch.

Coding TCs' Written Analysis of Student Assessment Responses

The analysis of TCs written evaluations of student assessment responses focused on their responsiveness to student sensemaking within phenomenon-based assessments. Each teacher candidate analyzed six samples of student work, resulting in a total of 138 samples examined across 23 candidates. We systematically coded the written analyses to explore how TCs noticed and interpreted student sensemaking and the evidence they used to support their conclusions. The codes and sub-codes that emerged from this analysis are presented in Table 2.

Table 2

Overall Codes for Analyzing TCs' Assessment Items and Written Analyses of Student Work

Categories	Codes	Sub-codes	Descriptions of codes
Opportunities: eliciting & probing student ideas/initial explanations	Substance of the assessment	Phenomenon	Presence/absence of phenomenon in assessment item If & how assessment was grounded in phenomenon
		Open-ended	Asking for explanations & mechanisms underlying phenomenon
		Closed	Assessment centered on factual/canonical knowledge
Noticing & interpretation: analysis of student responses, noticing of when & how students sensemaking occurred	TCs written analysis of student work	Procedural skill	Engaging students in label/draw/circle responses
		Sensemaking	sensemaking as ability to reason, hypothesize, or construct causal explanations as evidenced by analysis of responses. Students' leveraging from learning experiences cited as source of sensemaking
		TCs Describing observations	Sensemaking interpreted as ability to make & describe observations
		TCs Interpreting prior experiences	Experience as source for sensemaking, rather than evidence from analysis
		TCs making Inferences	Inferring & extrapolating student ideas based on students' work & responses
		TCs noticing the extent to which a student responded to the assessment-partially/completely	Sensemaking as ability to respond to assessment partially or completely
		Correct/Incorrect	Response to assessment
Responding: TC suggesting changes in assessment & instructions	TCs written analysis of student work	Task-based changes	Suggesting linguistic, social, & logistical changes in assessment
		Conceptual changes	Suggesting changes in support of sensemaking
		Task-based changes	Addressing linguistic, social, & logistic changes
		Conceptual need-based changes	Addressing conceptual idea for enhanced student sensemaking through lesson adjustment

The first category, Opportunities, emphasizes how TCs engaged with student ideas and initial explanations, specifically regarding the grounding of assessments in scientific phenomena. The second category, Noticing & Interpretation, captures TCs' analyses of student responses, focusing on their observations of when and how student sensemaking occurred. Finally, the Responding category highlights TCs' suggestions for changes in assessments and instruction based on their evaluations of student work. This structured approach provided valuable insights into TCs' understanding of student sensemaking and their capacity to adapt assessments to better support student learning.

Findings

We present our findings, reflecting on what we learned from analyzing the assessment tasks designed by TCs, and the ways in which they noticed, interpreted, and responded to students' sensemaking based on these assessments.

Approximately one-third (seven out of 23) of the TCs implemented an assessment design centered around a scientific phenomenon. This open-ended approach allowed for a wide range of student responses. In contrast, the remaining TCs either did not incorporate a phenomenon into their assessment design or, if they did, failed to utilize it effectively as a guiding element. Consequently, their assessments lacked the necessary framework of a guiding phenomenon, resulting in a dearth of opportunities to collect student ideas related to the phenomenon. TCs predominantly posed questions aimed at recalling canonical information or employed closed-ended inquiries that served only to confirm information, lacking any open-ended engagement. Table 3 provides a visual representation of these categories along with relevant examples for reference.

Table 3

Categories of TCs Based on Phenomenon and Substance of Assessment

Substance of Assessment	Phenomenon	Phenomenon aligned to assessment	Substance of the assessment (open-ended/ closed)
No phenomenon (Weak)	x	x	unproductive
	x	x	unproductive
	x	x	unproductive
	x	x	unproductive
	x	x	unproductive
	x	x	unproductive
	x	x	unproductive
	x	x	unproductive
	x	x	unproductive
Phenomenon is present, it is not utilized to facilitate student sensemaking (Moderate)	√	x	unproductive
	√	x	unproductive
	√	x	unproductive
	√	√	unproductive
	√	√	unproductive
	√	√	unproductive
	√	√	unproductive
Phenomenon present assessment aligned, Open-ended (Strong)	√	√	Productive
	√	√	Productive
	√	√	Productive
	√	√	Productive
	√	√	Productive
	√	√	Productive
	√	√	Productive

TCs Noticing and Interpretation of Student Responses

Recall that each of the 23 TCs analyzed the work of six students in response to the assessment item they implemented in their classrooms. TCs noticing and interpretation of student sensemaking were closely linked to the extent to which candidates used the phenomenon to guide the assessment. The largest group of TCs (nine out of 23) designed assessments that primarily engaged students in recalling and reproducing information, as well as defining vocabulary related to the science content concepts (Table 3). The design of these assessments was coded unproductive, meaning, it did not allow meaningful opportunities for students to show reasoning and construct mechanistic science explanations. The assessments mainly asked students for actions such as label, draw arrows, or follow a procedure. TCs who did not have a phenomenon guiding the assessment, and an unproductive assessment, mainly noticed student sensemaking as a matter of their behavior and attitude. These TCs mainly viewed student talking, alertness, and ability to answer correctly to various parts of the assessment as a proxy for sensemaking. These TCs repeatedly interpreted the students' ability to engage in this form of sensemaking as a manner to leverage their prior knowledge, whether from schooling or personal background. TCs engaged in limited interpretation because they could not gather many student ideas in the first place.

Some TCs (seven) successfully used phenomenon to guide assessment, however, the assessment was still limited in ways to elicit students' ideas regarding the phenomenon. Very characteristic of these candidates was their tendency to make extrapolated claims about students' understanding of the phenomenon based on their responses. TCs frequently noticed the students' ability to follow procedures as a process of sensemaking. Again, there were limited student ideas to notice and interpret. The assessments mainly used phenomenon as a hook or an interesting scenario while still probing to follow procedures like drawings, circling pictures, using arrows, etc.

The remaining seven TCs in this study were able to use science phenomena to guide their assessments, designing items that were productive to varying extents in probing students' construction of explanations, collecting data and observations, and responding to the relevant parts of the assessment based on those observations. TCs in this group noticed student ideas in relation to the phenomenon, which were mainly of cause-and-effect nature. These TCs engaged in richer analyses of student responses and provided evidence of student sensemaking from their work. The interpretation involved discussing learning opportunities from the two-day lesson as well as within the context of the assessment that led to supporting student sensemaking.

Suggesting Changes to Assessment

TCs reflected on the design and structure of the assessments after analyzing six sample responses of their students to the assessment item, considering how their noticing/ interpretations could inform future teaching practices. Out of the candidates, only three suggested changes to the assessments that were truly productive, meaning these adjustments had the potential to create more opportunities for student sensemaking in future lessons. In most cases, however, TCs struggled to propose meaningful adaptations. Their suggestions tended to be generic and focused on superficial changes, such as adding more content, incorporating additional vocabulary, or altering the sequence of activities and the structure of worksheets. While these adjustments might have eased transitions or improved comprehension, TCs primarily addressed structural issues rather than fostering deeper student engagement or understanding.

This tendency to focus on structural modifications suggests a gap in the TCs' ability to connect their assessments to the specific learning needs of their students. Instead of facilitating opportunities for richer sensemaking experiences, their recommendations often fell short of promoting critical thinking or deeper conceptual understanding. By failing to leverage insights gained from students' assessment responses, many candidates missed the chance to create more dynamic and responsive instructional strategies that could enhance student learning.

We had limited data on this aspect. Only one prompt asked TCs to reflect on any adaptations they made to the assessment based on what they noticed and interpreted from students' work. TCs reflections were generally shorter compared to their more elaborate analyses of the six student samples, which provided more opportunities for noticing and interpreting student thinking.

Examining Patterns Through Illustrative Examples

In this section, we illustrate model examples to provide a comprehensive picture of how phenomenon-based assessments influenced TCs' noticing and interpretation of student sensemaking. Examples also highlight the significant role phenomena play in TCs' noticing and interpretation of students' responses.

Example 1: TCs with No Phenomena and Close-Ended Assessments

In this case, the teacher candidate designed an assessment for first-grade students, targeting the NGSS performance expectation 2-PS1-1: Plan and conduct an investigation to describe and classify different kinds of materials by their observable properties. This expectation encourages students to observe materials based on properties like color, texture, hardness, and flexibility, and identify patterns among materials with similar properties.
The assessment item, shown in Figure 3, asked students to observe two solids and record their physical characteristics on a worksheet.

Figure 3

Example of a Recall-Based Assessment Not Grounded in a Phenomenon

Name:________________

Two New Solids

	Block	Paper Clip
color		
shape		
hardness		
rolls		
stacks		
magnetic		
float or sink		

Figure 4 shows students' responses to a recall-based assessment. While this task required students to engage in basic observational skills, it offered limited opportunities for deeper sensemaking. The closed-ended and somewhat vague nature of the task constrained students' ability to reason through their observations or construct meaningful explanations. As a result, the task emphasized procedural compliance over conceptual understanding. This was reflected in the TCs' noticing, which centered primarily on students' ability to follow directions, make surface-level observations, and categorize materials—without delving into the underlying reasoning processes or encouraging richer student dialogue (. The following reflections from the teacher candidate further illustrate these observations and offer insight into how they interpreted the assessment's impact on student learning.

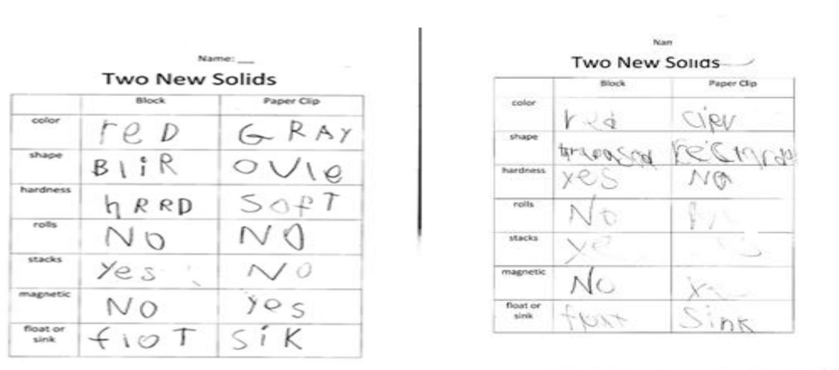
> This student seemed to show understanding in each area of assessment I was looking at. All of the spaces in the chart will be filled with reasonable and correct answers. On the back the student answered question one, offering the block because it stacks better. And for number two she came up with a pencil and wood are other solids that are similar to the block. Based on these items Focal Student 1 is meeting my assessment objectives. He filled out the entire

observation sheet with thoughtful and reasonable answers. For one box in the observation sheet, he said the paper clip was soft. I do not think this is an ideal answer, however comparatively to the block he may have concluded it was not as hard, so I still accept that answer as reasonable for showing understanding.

However, TCs interpretation of the student's sensemaking was mainly focused on the student's ability to match correct answers, rather than on how the student reasoned through the scientific concepts involved. For instance, when the student described the paperclip as "soft," the candidate accepted this as reasonable, interpreting the response as relative to the block, which the student might have perceived as harder. Although this acceptance allowed some flexibility in evaluating understanding, the candidate still concentrated on the correctness of the response rather than delving into how the student arrived at this conclusion or the quality of their reasoning. As a result, the interpretation was somewhat superficial, focusing on whether the students could describe objects and complete the chart correctly, rather than engaging with the complexity of how students reasoned through their observations and made sense of the materials.

Figure 4

Examples of Student Work Samples in Response to Recall-Based Assessment Not Grounded in a Phenomenon


Name: __

Two New Solids

	Block	Paper Clip
color	reD	GRAY
shape	BliR	oVle
hardness	hRRD	SofT
rolls	No	NO
stacks	Yes	NO
magnetic	NO	yes
float or sink	fioT	siK

Two New Solids

	Block	Paper Clip
color	red	[illegible]
shape	[illegible]	[illegible]
hardness	yes	NO
rolls	No	[illegible]
stacks	yes	
magnetic	No	[illegible]
float or sink	flot	Sink

The candidate suggested generic adaptations/changes to the assessment. For instance, the candidate suggested:

> After reviewing all of the responses I got on my assessment there are a few things I may change to get a better picture of the students' progress towards mastering the learning goals. One thing would be to provide a picture or visual next to each of the properties on the observation chart as a scaffolding.

For example, the teacher candidate proposed adding pictures or visuals next to the properties on the observation chart as a form of scaffolding. While this might improve accessibility and comprehension for students, it is a structural change that does not directly enhance the opportunities for deeper sensemaking or reasoning. The suggestion focuses more on supporting students in completing the task accurately, rather than fostering their ability to engage in more meaningful scientific thinking or explanation-building.

Overall, the candidate's noticing and interpretation of student responses reflected a focus on correct answers and procedural completion, rather than on probing the quality of students' sensemaking. The suggested adaptations similarly centered on improving task accessibility, rather than creating opportunities for richer exploration and understanding of scientific concepts.

Example 2: Phenomenon-Guided Assessment with Some Level of Open-Ended Questions

This example is typical of the TCs whose assessment item was guided by a phenomenon and included some opportunities for open-ended responses. While the assessment still had structured components, it allowed students some flexibility in reasoning and constructing explanations based on their observations of the phenomenon.

In this example, the phenomenon of flooding aligned well with the NGSS performance expectation 5-ESS2-1: Develop a model using an example to describe ways the geosphere, biosphere, hydrosphere, and/or atmosphere interact. This standard emphasizes understanding how Earth's systems (geosphere, biosphere, hydrosphere, and atmosphere) interact, and flooding could be used to illustrate how the hydrosphere (water) impacts the geosphere (land), biosphere (living organisms), and atmosphere (weather and climate). This provides students with the opportunity to think about complex systems and real-world connections between these spheres.

However, despite the selection of a well-chosen phenomenon, the assessment designed by the teacher candidate—shown in Figure 5—did not fully capitalize on the richness of the phenomenon and instead resembled a reading comprehension exercise.

Figure 5

Example of a Closed-Ended Assessment Item Grounded in a Phenomenon

Extreme weather conditions

Floods

Floods happen after or during heavy rainfall. This excess of water can damage peoples' property, damage roads and even wash cars away.

Flooding can be very dangerous to people. If flooding happens quickly without warning people can sometimes become stranded and have no way of escape. They have to be rescued from their rooftops or even from car roofs.

A severe weather warning helps prepare people for heavy rain and flooding. People try to protect their properties using sandbags stacked up against their doors to prevent water coming into their homes.

Rivers can sometimes burst their banks so people living in low lying areas or near rivers are more at risk from flooding. Often if heavy rain is forecast these areas are evacuated before the floods arrive.

Some scientists say that because of global warming, Britain will suffer more heavy rainfall and floods.

Questions

1 What can heavy rainfall cause? ________

2 Do floods usually occur in lowlands or highlands? ________

3 Describe how floods can be dangerous to people: ________

4 What can happen to rivers during a flood? ________

5 What do some scientists say is causing more floods in Britain? ________

6 What are sandbags used for? ________

7 What can help people prepare for heavy rain? ________

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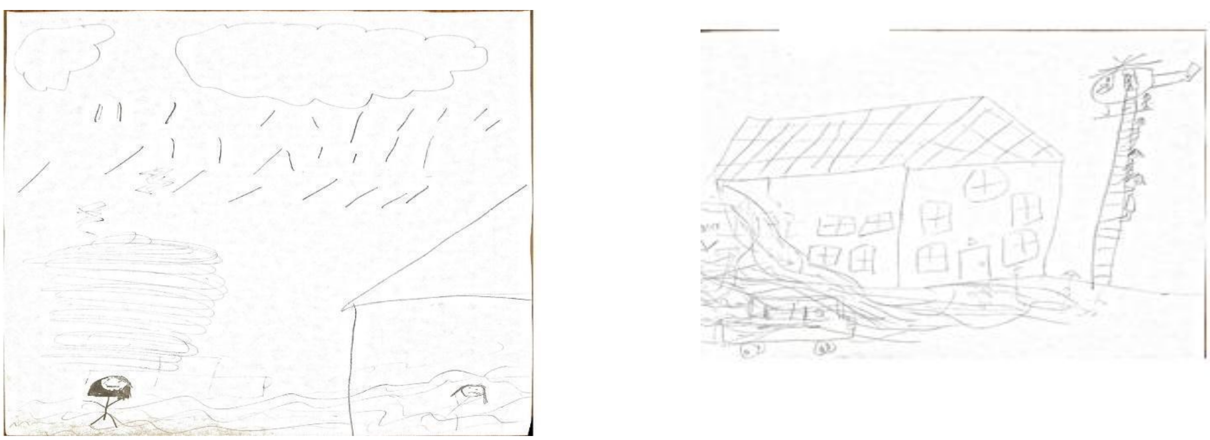
The assessment primarily consisted of closed-ended prompts, many of which were structured like reading comprehension questions. Instead of encouraging students to deeply engage with the phenomenon and reason through the interactions of Earth systems, the assessment relied heavily on "what" questions that asked students to recall facts or provide straightforward answers.

For example, instead of open-ended questions that might encourage students to explain how flooding impacts both living and non-living parts of the environment or to construct models illustrating these interactions, the questions asked students to recall specific details. This limited the students' opportunities to demonstrate deeper sensemaking, reasoning, or explanation-building around the phenomenon. While the phenomenon of flooding offered rich potential for exploring complex interactions and student-driven inquiry, the closed-ended nature of the assessment constrained students' engagement with the content, reducing the opportunity for more open-ended reasoning and explanation.

However, candidate also asked students to draw a flooding scenario. Artifacts showing a flooding scenario produced by students are shown in Figure 6.

Figure 6

Examples of Student Work Samples in Response to Closed-Ended Assessment Item Grounded in a Phenomenon



This teacher candidate attempted to infer students' understanding based on their drawings. Student drawings were not accompanied by any reasoning prompts, still TCs' were able to interpret students' sensemaking, for example, this teacher candidate inferred the following from one student's drawing:

> Flood water seemingly flowing into a house and carrying away people, which shows knowledge of how strong the water flow can be and recognition of the damage that can occur.

Drawings can be helpful in capturing students' initial thinking, but they need to be accompanied by prompts that encourage students to explain their representations or link them to scientific ideas. For instance, the teacher candidate inferred that a drawing showing "flood water flowing into a house and carrying away people" demonstrated the student's knowledge of the force of water and its potential to cause damage. However, without additional explanations or reasoning, it was difficult to determine whether the student truly understood the scientific concepts of water force and its effects on landforms.

In this case, this teacher candidate, like others with similar assessment items, equated student attentiveness and the ability to ask questions with sensemaking:

> The student was asking clarifying questions to other students at the table and was attentive in watching the demonstrations.

TCs interpreted students' ability to draw from personal experiences and connect learning opportunities from the lesson they taught before the assessment to the phenomenon as sensemaking. However, they did not explicitly identify the specific evidence students used from these personal and lesson-based experiences to engage in sensemaking:

> This student seemed to be engaged in sense making through the worksheet and what he had read. When producing the drawing it was clear that he had utilized the worksheet and a fact that he had gained from it. The nature of his ideas seemed to stem from the video as well as how we had discussed living by a riverbank.

For example, this teacher candidate observed that the student was making sense of the flooding phenomenon through various lesson components, such as the worksheet, video, and discussion. The student's drawing was viewed as a final artifact that connected information from these learning opportunities, leading the teacher candidate to perceive the student as a successful sense-maker. However, the teacher candidate's interpretation lacked specific details about which ideas the student connected and how those ideas related to the lesson content.

The present example underscores the need for assessment designs that not only include a phenomenon but also explicitly prompt students to articulate their reasoning and reflect on their understanding. This approach would provide stronger evidence of student sensemaking. In this case, if the assessment had included prompts asking students to explain how their personal experiences, the video, and class discussions informed their drawings, the teacher candidate would likely have gained a more comprehensive view of the student's sensemaking process.

Example 3: Phenomenon-Based Assessment with Open-Ended Questions to Encourage Reasoning

The following example illustrates the case of a teacher candidate who was successful in articulating a phenomenon and planning an assessment which provided a richer context for student sensemaking of the science phenomenon. The case of the teacher candidate presented here used the following NGSS performance expectation for the lesson: 1-PS4-1: Plan and conduct investigations to provide evidence that vibrating materials can make sound and that sound can make materials vibrate. The assessment primarily focused on: Students making predictions of what the waves they see will look like and then recording what they saw. Figure 7 describes student responses to the assessment.

The lesson and assessment were centered on the scientific phenomenon of how sound affects matter. The teacher candidate provided students with various opportunities to observe sound waves traveling through different mediums. Students were prompted to predict outcomes and then record actual observations, encouraging them to share their thinking on how sound interacts with matter. Throughout the assessment, the teacher candidate consistently referred to students' ideas about the phenomenon, using these reflections as concrete evidence of student sensemaking. This teacher candidate also analyzed these ideas to draw conclusions about students' understanding of the phenomenon.

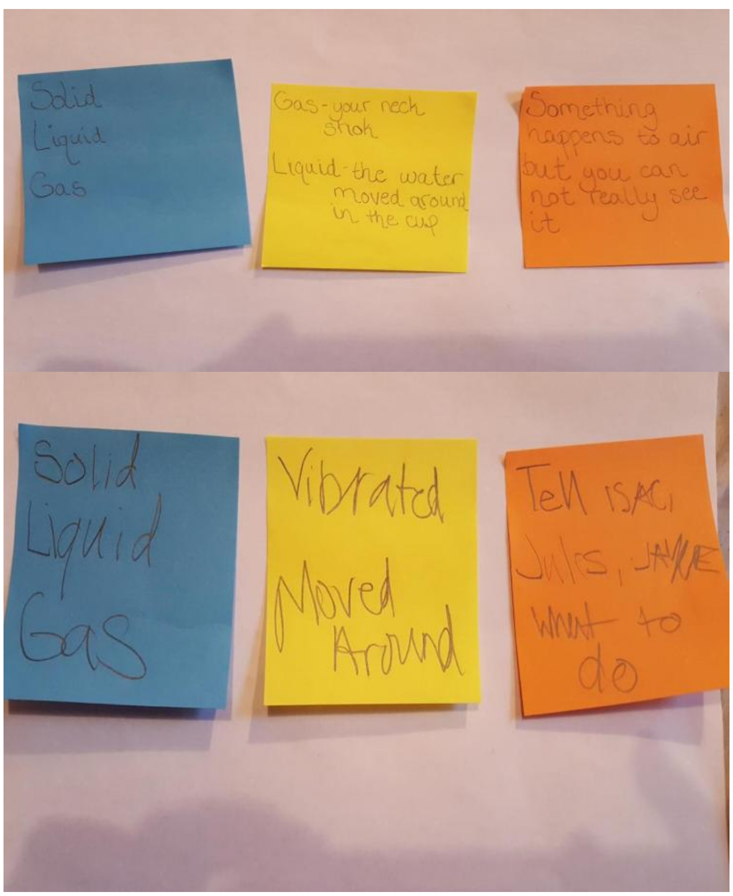
> This student was engaged in the sensemaking activity because she was using the water bottles to show us what she had learned within the experiment and what she had did. She showed us

> how the water moved and how you could see and feel that the water bottle was moving when sound was applied.
>
> This student was engaging during the sensemaking because she took what she had learned from the lesson and applied it to what she would learn in the future. She made the question to say is there an easier way to see that things move in the air? So this makes me think that she is thinking outside of the box and that she is thinking about how to extend her knowledge.
>
> I know that this student understands what happens when sound is applied to a state of matter because he said that that state of matter moves.

The quotes from this teacher candidate's reflection on individual students' responses reveal a strong focus on students' ideas. The teacher candidate noted how students used their classroom investigations to make sense of the phenomenon, and how some students generated questions based on their learning experiences as evidence of deeper sensemaking. This reflection highlights the TCs' attention to students as sense makers, and how they applied their experiences to understand the phenomenon of how sound affects matter.

Figure 7

Examples of Student Work Samples in Response to Assessment Item with Open-Ended Questions to Encourage Reasoning



Although the teacher candidate provided opportunities and noticed student ideas around the scientific phenomenon, the assessment did not effectively probe or offer scaffolds for students to express their mechanistic thinking. The focus on mechanistic thinking—reasoning about how and why things happen—was not emphasized in the assessment item. Like other TCs in the data set, the candidate in this example also struggled to respond productively based on their observations:

> I would change my assessment by having students fill out a worksheet with the same questions before the lesson to see what they know, and then fill it out again after to see if anything changes. I would do this to determine whether students are truly learning from the lesson or just filling out answers at the end to be done.

However, this adaptation was rather generic, as the teacher candidate suggests using a pre- and post-lesson worksheet to compare students' knowledge and see if they genuinely learned from the lesson or simply filled in answers to finish. However, this approach focuses on checking for changes in factual knowledge rather than probing students' deeper understanding or sensemaking.

Range in TCs' Noticing and Interpretation Across Assessment Examples

The design of assessments—whether they included a phenomenon or not, emphasized reasoning, or featured vague or open-ended questions—influenced TCs' ability to notice and interpret students' scientific ideas and disciplinary thinking. Although we did not directly study this as a research question, our analysis suggests a possible connection between the quality and structure of the assessments and the depth of TCs' noticing and interpretation. For example, TCs who designed assessments without a phenomenon (e.g., Example 1) tended to ask questions that provided little to no opportunity to interpret students' thinking. In these cases, their noticing and interpretation often overlapped, with interpretation leaning heavily on whether a student's response was correct. These candidates tended to equate sensemaking with correctness and missed opportunities to identify moments where students were actively trying to construct understanding.

In contrast, assessments that included a phenomenon but had vague or limited questioning (e.g., Example 2) emphasized the importance of preparing TCs to ask meaningful, student-accessible questions. Without strong questioning strategies, even a phenomenon-rich task may not yield deep insight into student thinking or provide opportunities for sensemaking. Finally, in assessments that combined a well-grounded phenomenon with purposeful questioning (e.g., Example 3), TCs were more successful in noticing students' ideas and offering interpretations that recognized authentic moments of sensemaking. These candidates not only attended to individual student reasoning but also considered how students interacted with peers as they worked to make sense of the phenomenon together. This range of assessment examples underscores the importance of supporting TCs in designing assessments that are both anchored in meaningful phenomena and structured to elicit and interpret students' thinking in responsive ways.

Discussion

The study revealed that many TCs struggled to ground their assessments in phenomena (Reiser, 2013). Even those who managed to identify a relevant phenomenon often found it difficult to design open-ended assessments that would elicit students' sensemaking and deeper thinking (Furtak & Ruiz-Primo, 2008; Gotwals & Birmingham, 2016). TCs who developed somewhat open-ended assessments still faced challenges incorporating probing questions that encouraged students to articulate their reasoning, both orally and in writing. These findings highlight that TCs need support and course learning opportunities to help them develop well-aligned, phenomenon-based assessments that foster students' sensemaking (Pellegrino et al., 2014). This alignment is essential for creating opportunities to gather and interpret a broad range of student ideas and thinking.

One possible reason for these challenges could be the influence of traditional notions of assessment, where assessments are often viewed primarily as tools to determine whether students have the "correct" information, rather than as opportunities to elicit and analyze diverse forms of student thinking (Otero, 2006). Additionally, TCs need learning opportunities that emphasize the importance of student reasoning, particularly in helping students engage with mechanistic thinking. A persistent misconception among teachers is that young learners, especially in elementary grades, are not capable of engaging in scientific explanations. However, research shows that even young learners can reason mechanistically when provided the opportunity (Metz, 2004, 2011; NRC, 2007). Overcoming these traditional beliefs is critical for TCs as they learn to design assessments that allow students to make sense of phenomena at a deeper level (Russ et al., 2009).

Course learning opportunities in our program were intentionally designed to address these areas by emphasizing the value of reasoning, student ideas, and three-dimensional learning in science instruction. However, these shifts remain challenging for TCs, as they continue to encounter traditional approaches to science teaching during their observations and student teaching in K–5 classrooms. While a methods course, like the one which made for the context of this study, can establish a good foundation for understanding phenomenon based three-dimensional learning, induction and sustained professional development is needed to rehearse and continue building on this understanding.

This study adds to the literature by focusing on preservice elementary science teachers and how phenomenon-based assessment structures can serve as a lever for deepening their noticing and response to students' ideas, reasoning, and use of scientific practices. Specifically, we position our work within ongoing efforts to better understand how TCs develop the ability to notice and interpret students' sensemaking—TCs must come to view assessment not only as a means to evaluate learning, but as a way to gather, interpret, and build from students' thinking (Pellegrino et al., 2014). When TCs used phenomenon-based assessments accompanied with open ended reasoning-based questions to access students' ideas they move beyond simply checking for correctness; instead, they noticed and interpreted students' thinking. The design of assessments played a critical role in this process. Therefore, preparing TCs to design and use assessments that prioritize sense-making, explanation, and conceptual reasoning is key to responsive teaching.

Overall, TCs in science methods courses need scaffolding throughout various stages of the assessment design process. First, they need learning opportunities to develop phenomena-based assessments with relevant open-ended driving questions (Harris et al., 2012). Additionally, they need to understand the purpose of such assessments to gather diverse student ideas and provide students with opportunities to show and apply their thinking, use evidence to explain their ideas, and demonstrate their understanding (Windschitl et al., 2012). Engaging TCs in analyzing student work samples from open-ended assessments can help them practice noticing and interpreting a range of student thinking patterns (Benedict-Chambers & Aram, 2017). TCs must learn to notice and interpret this range of student thinking and use that information to guide their instruction. Expanding TCs' understanding of the purpose of assessments and how assessment design impacts student learning is critical to achieving the goals of fostering student sensemaking in science education.

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References

Benedict-Chambers, A., & Aram, R. (2017). Tools for teacher noticing: Helping preservice teachers notice and analyze student thinking and scientific practice use. *Journal of Science Teacher Education*, *28*(3), 294-318.

Berland, L. K., & Reiser, B. J. (2009). Making sense of argumentation and explanation. *Science Education*, *93*(1), 26-55.

Brown, L. P., & Bybee, R. W. (2023). Promoting sensemaking through an impactful instructional sequence. *The Science Teacher, 90*(6), 22-27.

Campbell, B. K. (2018). Toward more student-centered instruction: The advent of teacher noticing and responsiveness in mathematics and science education research. *The William & Mary Educational Review, 6*(1), 3.

Davis, E. A., Kloser, M., Wells, A., Windschitl, M., Carlson, J., & Marino, J. C. (2017). Teaching the practice of leading sensemaking discussions in science: Science teacher educators using rehearsals. *Journal of Science Teacher Education, 28*(3), 275-293.

Furtak, E. M., & Ruiz-Primo, M. A. (2008). Making students' thinking visible in written explanations: An instructional strategy for elementary science classrooms. *Journal of Research in Science Teaching*, *45*(6), 748-769.

Furtak, E. M., Thompson, J., & van Es, E. A. (2016, April). Formative assessment and noticing: Toward a synthesized framework for attending and responding during instruction. In *Annual Meeting of the American Educational Research Association*, Washington, DC.

Furtak, E., Kang, H., Pellegrino, J., Harris, C., Krajcik, J., Morrison, D., & Wingert, K. (2020). Emergent design heuristics for three-dimensional classroom assessments that promote equity. *Journal of Research in Science Teaching*, *57*(7), 992–1027. https://doi.org/10.1002/tea.21623

Gotwals, A. W., & Birmingham, D. (2016). Eliciting, identifying, interpreting, and responding to students' ideas: TCs' challenges across content areas. *Journal of Teacher Education*, *66*(1), 21-38.

Hammer, D., & Van Zee, E. (2006). *Seeing the science in children's thinking: Case studies of student inquiry in physical science*. Heinemann.

Hanuscin, D. L., & Zangori, L. (2016). Developing practical knowledge of the Next Generation Science Standards in elementary science teacher education. *Journal of Science Teacher Education, 27*(8), 799-818.

Harris, C. J., Phillips, R. S., & Penuel, W. R. (2012). Examining teachers' instructional moves aimed at developing students' ideas and questions in learner-centered science classrooms. *Journal of Science Teacher Education, 23*(7), 769-788.

Hutchison, P., & Hammer, D. (2010). Attending to student epistemological framing in a science classroom. *Science Education, 94*(3), 506-524.

Johnson, H. J., & Cotterman, M. E. (2015). Developing preservice teachers' knowledge of science teaching through video clubs. *Journal of Science Teacher Education*, *26*(4), 393-417.

Kang, H., Thompson, J., & Windschitl, M. (2014). Creating opportunities for students to show what they know: The role of scaffolding in assessment tasks. *Science Education, 98*(4), 674–704.

Kang, H., & Anderson, C. W. (2015). Supporting preservice science teachers' ability to attend and respond to student thinking by design. *Science Education, 99*(5), 863-895.

Luna, M. J. (2018). What does it mean to notice my students' ideas in science today? An investigation of elementary teachers' practice of noticing their students' thinking in science. *Cognition and Instruction, 36*(4), 1-33. https://doi.org/10.1080/07370008.2018.1496919

Luna, M. J., & Sherin, M. G. (2017). Using a video club design to promote teacher attention to students' ideas in science. *Teaching and Teacher Education, 66*, 282-294. https://doi.org/10.1016/j.tate.2017.04.020

Metz, K. E. (2004). Children's understanding of scientific inquiry: Their conceptualization of uncertainty in investigations of their own design. *Cognition and Instruction, 22*(2), 219-290.

Metz, K. E. (2011). Young children can be sophisticated scientists. *Phi Delta Kappan, 92*(8), 68-71.

National Research Council. (2007). *Taking science to school: Learning and teaching science in grades K-8*. National Academies Press.

National Research Council. (2012). *A framework for K-12 science education: Practices, crosscutting concepts, and core ideas*. National Academies Press.

Next Generation Science Standards. (2013). *Next Generation Science Standards: For states, by states.* National Academies Press.

Odden, T. O. B., & Russ, R. S. (2019). Defining sensemaking: Bringing clarity to a fragmented theoretical construct. *Science Education, 103*(1), 187–205

Otero, V. K. (2006). Moving beyond the "get it or don't" conception of formative assessment. *Journal of Teacher Education*, *57*(3), 247-255.

Pellegrino, J. W., Wilson, M. R., Koenig, J. A., & Beatty, A. S. (2014). *Developing assessments for the next generation science standards.* National Academies Press.

Penuel, W. R., & Bell, P. (2016). *Qualities of a good anchor phenomenon for a coherent sequence of science lessons.* University of Washington. http://stemteachingtools.org/brief/28

Reiser, B. J. (2013, September). What professional development strategies are needed for successful implementation of the Next Generation Science Standards. Paper presented at the Invitational Research Symposium on Science Assessment.

Russ, R. S., Coffey, J. E., Hammer, D., & Hutchison, P. (2009). Making classroom assessment more accountable to scientific reasoning: A case for attending to mechanistic thinking. *Science Education, 93*(5), 875-891.

Schwarz, C. V., Passmore, C., & Reiser, B. J. (Eds.). (2017). *Helping students make sense of the world using next generation science and engineering practices.* National Science Teachers Association Press.

Sherin, M., & van Es, E. (2005). Using video to support teachers' ability to notice classroom interactions. *Journal of Technology and Teacher Education, 13*(3), 475-491.

Windschitl, M., Thompson, J., Braaten, M., & Stroupe, D. (2012). Proposing a core set of instructional practices and tools for teachers of science. *Science Education*, *96*(5), 878-903.

Zembal-Saul, C., & Hershberger, K. (2019). Positioning students at the center of sensemaking: Productive grappling with data. In E. A. Davis, C. Zembal-Saul, & S. M. Kaemian (Eds.), *Sensemaking in Elementary Science* (pp 15-30). Routledge.

Annexure 1

Assessment and Data Collection Plan Lesson Design & Analysis

In the previous assignments you a) identified a topic, as well as appropriate NGSS Performance Expectations b) began framing your lesson in alignment with the NGSS and the Experiences, Patterns and Explanations model of teaching; and c) identified your students' prior ideas and experiences (sensemaking #2) in relation to the science content you will be teaching. In this assignment, you will lay out specific plans for ASSESSING your students' ability to meet the identified learning goals (NGSS) after teaching your lesson.

Assignment Template and Explanation:
Name(s):
Grade Level:
Targeted Learning Goals:
Copy this section from your Framing assignment. (Lesson Identification and Learning Goal)

Post Assessment Task
Design ONE brief assessment task that will provide rich information about your students' thinking and understanding for your unit learning goals. ***Include a copy of your assessment task in this assignment.*** *Rich tasks should involve the students in creating a somewhat elaborate response, not just giving a one-word answer. It should involve the students carrying out the practices defined in your learning goal, not just recalling information. It should provide an opportunity to apply a main idea, not just recall or recognize it. Examples of rich tasks include performance assessments such as providing students with a variety of objects, asking them to use those objects to construct or do something and asking them to explain how the science ideas are important in their decisions to meet that goal. You can engage students in figuring things out, finding patterns, using their explanations to justify their decisions in written response items. You can use a variety of other assessments such as observing students as they work in groups, analyzing their drawings, labels and explanations in their science notebooks, or even a task that is already in your instructional materials.*

Here are some hints for designing a "rich" assessment task:

- *Your assessment task should be closely aligned with your NGSS Performance expectation.*
- *Your assessment task should engage students in meaningful and thoughtful work. They should be applying a big idea from your lesson and carrying out practices/cross-cutting concepts defined in your NGSS Unpacking and related knowledge & skills, not just recalling or listing information and ideas.*
- *Students should provide an elaborate response, not a one-word answer.*
- *Analysis of your students' responses should provide you with information about their strengths and weaknesses with respect to your assessment objective. This should go beyond whether students "got" your assessment objective and whether they participated in your lesson and/or the task.*
- *All students should be able to respond to your task, perhaps with varying degrees of quality. (If some students cannot respond at all, you miss the opportunity to find out what they do understand.)*

Post Assessment Task Rationale
Write a brief statement explaining what this assessment task will allow you to learn about how much and how deeply your students understand your lesson NGSS Performance Expectation. What specific skills, ideas and practices are you trying to assess in this task? (Include how you are addressing your SEP/DCI/CCC in your assessment.)

Scoring Guide for Analyzing Students' Responses to the Post Assessment Task

Next, you will need to determine how you will analyze and interpret the students' responses to your task. Analyzing students' responses can be done by identifying features in their responses that you can look for and document. You will create a scoring guide that thoroughly describes all of the desired features of students' responses that would indicate the extent to which they have met your assessment objective. Your scoring guide should include the ***specific details*** *you would look for in a student's response that will let you know what aspects they know well, what aspects they struggled with, and how they were reasoning about your task.*

These features can be used to evaluate how much your students have learned the lesson content and how deeply they have understood it. The essential features represent the criteria you will use to analyze your students' responses on the post assessment after your lead teaching. These features will provide the starting point for your analysis after the post assessment – but you may find that you'll make some changes to these as a result of seeing the kinds of responses your students provide on the post assessment task.

Note: If there are important aspects related to the learning goal (i.e., main ideas students should know, practices students should be able to do) that you cannot evaluate based on your task, you may need to add to or change your task so that it will provide sufficient evidence to help you decide how well your students are meeting the learning goal.

Grading Criteria:

	Desired Features	**Points**
Post Assessment Task and Rationale	• The assessment objective matches the NGSS Performance Expectations. • The assessment task engages students in opportunities to use knowledge gained from SEP/DCI/CCC for elaborated responses. • The assessment objective describes a behavior that demonstrates a deep understanding of the learning goal. (not rote memorization, multiple choice, fill in the blank, etc.) • The assessment task is likely to elicit rich information that will allow evaluation with respect to the assessment objective. • The assessment task is accessible to students with a range of mastery (above and below expected levels of performance) of the assessment objective. • The rationale clearly explains how the assessment task assesses the students' understanding of the NGSS Performance Expectation. • The rationale clearly explains what the assessment task is intended to show regarding students' understanding of the NGSS Performance Expectation – including opportunities for illuminating possible misconceptions or advanced ideas.	/5

Post Assessment Rubric/Scoring Guide	• There is a clear plan for analyzing students' responses to the assessment task, including the way in which results can be used to reflect upon students' strengths and weaknesses (and not just whether they are "right" or "wrong".) • The scoring guide includes the **specific details** teachers should look for in a student's response. • The scoring guide provides students with an opportunity to give their explanations and reasoning related to the task.	**/5**

Annexure 2

Analysis of Classroom Interactions, Student Learning, & Reflection Final Segment of Lesson Design & Analysis

This assignment is designed to support you in analyzing evidence from teaching your lesson in your field placement and in reflecting on your teaching.

Preparing for the Assignment

In order to successfully complete this assignment, you will need to collect a video or audio recording of your lesson and take detailed notes after teaching to have as much information about the nature of your lesson as possible. You will also need assessment responses or samples of student work from six students including the focal students in your placement classroom during the time that you teach your lesson. Your reflections should be detailed and specific, and should focus on the evidence from the recordings/notes and from student work.

Assignment Directions

There are several parts to this assignment. You will be providing a detailed response for each part that is well supported with specific examples from the recording of your lesson, your students' work and your teaching notes.

Analysis of Whole Class Interactions and Classroom Culture

Carefully review your video/audio recording of your lesson and the detailed notes. Analyze and evaluate classroom community and interactions in the lesson using evidence from your recordings. Below, you will write a detailed, multi-paragraph analytical response for each of the following questions: *What opportunities did students have to participate and engage in the lesson? How did they participate? How were students' resources (e.g., funds of knowledge, ways of knowing) elicited and leveraged? How did students interact with each other and you as the teacher?*

Analysis of Individual Learning from Student Work

Work with your instructor to decide how to choose sample student work. Carefully review evidence from identified focal and other students about student learning including their actions and talk as well as their work in the assessment. You will analyze student work using the assignment template (below), and write a detailed, multi-sentence analytical response for each of the following questions: *In what ways did students engage in sensemaking? In what ways did their work indicate they are not meeting, partially meeting, or meeting the learning goal?*

Reflections on Analysis and Teaching

Review the analysis and findings from above regarding whole class interactions and student learning in addition to your notes from teaching. Then, you will write a detailed response to reflection questions about *your overall impression of strengths and weaknesses of the lesson, how the lesson plan addressed diverse student learners, the strengths and limitations of the assessment, and how this experience impacted your teaching identity.*

Implications for Future Teaching

Review the analysis and findings from above regarding whole class interactions and student learning in addition to your notes from teaching. Then, you will write a detailed response to the questions: *Given the analysis of interactions and student learning, describe your written and oral feedback you would provide your focal and other students to advance their science learning. How would you teach this same lesson again to improve the lesson and why?*

Assignment Template
The next part of this assignment is the assignment template to help guide you in your analysis and reflections

Name(s):

Lesson Topic and Grade Level:

- **PERFORMANCE EXPECTATION:**
    - **NARROWED LESSON FOCUS:**
    - **SCIENCE AND ENGINEERING PRACTICE**:
    - **CROSSCUTTING CONCEPT**:

Phenomenon and Driving Question for Lesson:
Identify a phenomenon and write a driving question designed to support students' developing understanding of your learning goals. Your driving question should be directly aligned with the NGSS Performance Expectation, have a real-world context, and demonstrate a deep understanding of the learning goal when answered. See course slides for examples of how to identify a phenomenon and write a driving question.

PHENOMENON:

DRIVING QUESTION:

1. **Analysis of Whole Class Interactions and Classroom Culture**

    Write a detailed, multi-sentence analytical response for each of the following questions:

    a. What opportunities did students have to participate and engage in the lesson? Examples include talk, interactions with materials, etc. **How did students participate?** (e.g., who was doing the talking, what kind of language were they using?)

    b. How did you elicit and leverage students' resources (e.g., funds of knowledge, ways of knowing)**?**

    c. How did students interact with each other and you as the teacher? (e.g., how were their ideas responded to, were they acknowledged, rejected or built on, whose ideas were taken up and whose were not?)

2. **Analysis of Individual Learning from Student Work**

    Assessment Objective:

    Desired Assessment Features/Scoring Guide:
    [list the features you identified in your LDA #1-2 assessment assignment for evaluating student work.

Focal Student 1 **Brief description for why you chose this student's work.** **Description of the student's interactions/engagement including their talk (e.g., what they said) during the lesson.** **Photo of student work sample(s):**	**Focal Student 1** **Evidence of sensemaking:** *Describe how this student was engaged in sensemaking. What resources were they using? What was the nature of their ideas, reasoning, experiences, and how did they use those to address the lesson topic?* **Evidence from work sample of student learning:** *List features you have identified in your student work sample that indicate student understanding of the learning goal. Provide a claim for what this indicates about student understanding and a rationale of why this demonstrates that they are not meeting, partially meeting, or meeting your NGSS assessment objective.*
Focal Student 2 **Brief description for why you chose this student's work.** **Description of the student's interactions/engagement including their talk (e.g., what they said) during the lesson.** **Photo of student work sample(s):**	**Focal Student 2** **Evidence of sensemaking:** *Describe how this student was engaged in sensemaking. What resources were they using? What was the nature of their ideas, reasoning, experiences, and how did they use those to address the lesson topic?* **Evidence from work sample of student learning:** *List features you have identified in your student work sample that indicate student understanding of the learning goal. Provide a claim for what this indicates about student understanding and a rationale of why this demonstrates that they are not meeting, partially meeting, or meeting your NGSS assessment objective.*
Focal Student 3 **Brief description for why you chose this student's work.** **Description of the student's interactions/engagement including their talk (e.g., what they said) during the lesson.** **Photo of student work sample(s):**	**Focal Student 3** **Evidence of sensemaking:** *Describe how this student was engaged in sensemaking. What resources were they using? What was the nature of their ideas, reasoning, experiences, and how did they use those to address the lesson topic?* **Evidence from work sample of student learning:** *List features you have identified in your student work sample that indicate student understanding of the learning goal. Provide a claim for what this indicates about student understanding and a rationale of why this demonstrates that they are not meeting, partially meeting, or meeting your NGSS assessment objective.*
(Focal) Student 4 **Brief description for why you chose this student's work.** **Description of the student's interactions/engagement**	**(Focal) Student 4** **Evidence of sensemaking:** *Describe how this student was engaged in sensemaking. What resources were they using? What was the nature of their ideas, reasoning, experiences, and how did they use those to address the lesson topic?* **Evidence from work sample of student learning:**

including their talk (e.g., what they said) during the lesson. **Photo of student work sample(s):**	*List features you have identified in your student work sample that indicate student understanding of the learning goal. Provide a claim for what this indicates about student understanding and a rationale of why this demonstrates that they are not meeting, partially meeting, or meeting your NGSS assessment objective.*
(Focal) Student 5 **Brief description for why you chose this student's work.** **Description of the student's interactions/engagement including their talk (e.g., what they said) during the lesson.** **Photo of student work sample(s):**	**(Focal) Student 5** **Evidence of sensemaking:** *Describe how this student was engaged in sensemaking. What resources were they using? What was the nature of their ideas, reasoning, experiences, and how did they use those to address the lesson topic?* **Evidence from work sample of student learning:** *List features you have identified in your student work sample that indicate student understanding of the learning goal. Provide a claim for what this indicates about student understanding and a rationale of why this demonstrates that they are not meeting, partially meeting, or meeting your NGSS assessment objective.*
(Focal) Student 6 **Brief description for why you chose this student's work.** **Description of the student's interactions/engagement including their talk (e.g., what they said) during the lesson.** **Photo of student work sample(s):**	**(Focal) Student 6** **Evidence of sensemaking:** *Describe how this student was engaged in sensemaking. What resources were they using? What was the nature of their ideas, reasoning, experiences, and how did they use those to address the lesson topic?* **Evidence from work sample of student learning:** *List features you have identified in your student work sample that indicate student understanding of the learning goal. Provide a claim for what this indicates about student understanding and a rationale of why this demonstrates that they are not meeting, partially meeting, or meeting your NGSS assessment objective.*

3. Reflections

Write a detailed, multi-sentence analytical response for each of the following questions:

Overall reflections (see tips for your reflections below):

1. What were some strengths of your lesson? Support your claims with evidence.
2. What were some weaknesses of your lesson? Support your claims with evidence.
3. How did your lesson support or not support student science learning? Support your claims with evidence.

Reflections on responsiveness to diverse students:

1. How did the lesson meet or not meet the needs of the students?
2. How did you adjust the lesson plan and teaching in response to students' contributions and sensemaking?

Reflections on assessment: In addition to analyzing student responses to your assessment task for clear evidence of student understanding, you will also need to reflect upon the effectiveness of your assessment.

1. What were the strengths of the assessment you chose for providing evidence of student science understanding? Explain why. Include evidence (e.g., one example; overall class responses).
1. What were the limitations of the assessment you chose for providing evidence of student science understanding? Explain why. Include evidence (e.g., one example; overall class responses).
1. Based on your analysis of the responses, what changes would you make for this assessment task in order to get a more complete picture of all students' progress towards mastering your science content NGSS learning goals? Why?

Reflections on classroom culture:

1. How did the lesson conform or deviate from the established classroom culture from the mentor teacher? How might that have impacted student interactions and learning?

Reflections on teacher identity:

1. How did teaching your lesson impact your own identity as a teacher and as a science learner?

4. Implications

Write a detailed, multi-sentence analytical response for each of the following questions:

1. If you were to give feedback to your six students whose work you analyzed, what would you write and say to help them learn and make better sense of the science? Provide specific text examples for each student and a rationale for the feedback.
2. If you were to teach this same lesson again, what changes would you make to your lesson plan to better support your students' science learning? Why?

Tips for your reflections

- As you are working on your reflections, take time to review the themes from the course. Reference and use these ideas in your responses.
- As you are reflecting on your science teaching and student learning, remember that this reflection is not about behavior management or constraints out of your control. Instead, we are asking you to focus on your planning, your teaching, students' engagement, and student learning.
- Be sure to use evidence in your analyses and reflections to support the statements you are making.
- Even if your lesson was highly successful, challenge yourself to consider something on which you could make improvements in the future. This is an important skill to develop as a life-long learner.

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Forging STEM Pathways for Black Girls: An Exploratory Analysis of High School, College, and Career Trends

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ABSTRACT

The purpose of this article is to characterize the science, technology, engineering, and mathematics (STEM) pipeline for Black adolescent female students by reviewing trends in (1) Advanced Placement (AP) test performance, (2) college enrollment decisions, (3) degree attainment, and (4) early career choices. This article examined quantitative trends across these four transition points in the STEM pipeline to inform the academic preparation of Black girls for success in postsecondary STEM endeavors. The findings from this review indicate that AP test participation and success often mirror Black female student STEM college major decisions. Yet, early STEM employment trends indicate many nuances that warrant further investigation. The theoretical and practical contributions of these data are noteworthy, given that the data presented are often alluded to but have yet to be synthesized and presented in a manner that informs practice. Based on these data, we provide recommendations for identifying, preparing, mentoring, and retaining Black women and girls in STEM.

Keywords: equity, diversity, Black adolescent girls, STEM, degree attainment, career interest

Introduction

Black girls have the potential to take advantage of STEM pathways to enter the Science, Technology, Engineering, and Mathematics (STEM) workforce. However, the empirical stories of academically advanced Black girls parallel their underrepresentation in advanced mathematics and science classrooms as well as in STEM professions (Collins et al., 2020). The existence of Black women within two traditionally underrepresented groups (i.e., Black and female) creates unique challenges and opportunities for their entrance into the STEM workforce. However, their potential cannot be realized until we better understand the STEM pathways Black girls take through K-12 and post-secondary schools. Due to a longstanding emphasis on the racial and gender achievement gaps throughout history, the majority of the information available regarding the academic performance of Black girls is derived from trends observed among Black students as a whole, or all girls in general. Rather, many scholars make assumptions or overgeneralizations due to a lack of data disaggregation and limited quantitative intersectional research dissemination. Scholars who examine the research around Black women and girls in STEM education have called for the use of intersectionality to better capture their unique experiences (Ireland et al., 2018). Quantitative intersectional research data are necessary because most reports present race and gender statistics dichotomously.

For example, according to the National Science Foundation (2016), 35.2% of chemists are women; 11.1% of physicists and astronomers are women; 33.8% of environmental engineers are women; 22.7% of chemical engineers are women; 17.5% of civil, architectural, and sanitary engineers are women; 17.1% of industrial engineers are women; 0.7% of electrical or computer hardware engineers are women, and 7.9% of mechanical engineers are women. But this raises the question of how many of these women are Black. This is an example of quantitative data that remains absent in STEM education. Pinpointing the representation of Black women in STEM careers is crucial for the K-12 education of Black girls because it provides Black girls and their parents with information on which STEM professions are more welcoming and more likely to have professional mentors to guide their academic and career success, a key factor in Black women and girls STEM persistence (Sendze, 2023). Here, we focus purely on Black women and girls by moving away from "gap-gazing," which focuses on the differences between Black and White students. Instead, we look at specific trends for Black women and girls (Young et al., 2017). Regarding the present study, what remains under-examined are trends in advanced placement (AP) learning outcomes, postsecondary enrollment, degree attainment, and STEM employment for Black women and girls. To inform educational practice, we examined trends across national datasets to characterize the progression of Black female learners through the STEM education pipeline, with an emphasis on these four critical time points in the STEM pipeline mentioned earlier.

Purpose

This article aims to explore critical points in the STEM pipeline for young Black women and girls, quantify specific "leaks," and provide recommendations for educational practice. For the present study, we will examine four critical points in the STEM pipeline: (1) high school preparation, (2) college enrollment, (3) degree attainment, and (4) employment. At each of these points, leaks often stem from the dual systemic discrimination Black girls face due to their race and gender. This synthesis of secondary data aims to elucidate trends in STEM preparation, college enrollment, degree attainment, and career pathways for Black women and girls. To this end, we examined four research questions, one for each critical point in the STEM pipeline. Our four research questions are presented below:

1. How is the STEM preparation of Black girls characterized by Advanced Placement (AP) exam participation and performance?
2. What are Black women's predominant professional intentions in STEM fields at the onset of their college education?
3. What are the longitudinal trends in STEM degree attainment among Black women over the past decade?
4. How are Black women represented across various STEM professions with respect to employment distribution?

In the following discussion, we argue that a data deficiency exists regarding specific numeric STEM data trends for Black women and girls. To fill this void, we examined trends across national data sets reflecting four critical points in the STEM pipeline: (a) high school, (b) college enrollment, (c) degree attainment, and (d) early career. We first review the relevant K-12 and post-secondary research literature on Black girls' STEM education, achievement, and career attainment. Next, we contextualize Black female progression through the STEM pipeline through the lens of the opportunity-propensity framework. The opportunity-propensity framework provides a conceptual model that we used to depict how three categories of factors (i.e., antecedent, opportunity, and propensity) afford and constrain the STEM attainment of Black girls. Then, we describe specific structural elements related to the three factors that have an acute influence on STEM attainment of Black women and girls. This is achieved by reviewing the related literature and drawing connections between the factors influencing the STEM degree attainment of Black women and girls in the opportunity-propensity model.

Next, we present the research methods used to analyze the national datasets and provide a rationale for using single-group summaries. Third, we expound on the results of the data summaries and provide implications for education praxis to support Black women and girls. These summaries represent data from the last decade from public use databases and national research centers that collect and report educational, occupational, and professional demographic data. Finally, we provide recommendations to support the identification, preparation, mentorship, and retention of Black women and girls in STEM education. The following discussion paints a compelling narrative about the systemic inequities, untapped potential, and resilience of Black women and girls in the STEM pipeline. It highlights critical issues across multiple stages of their educational and professional trajectories, presenting both challenges and opportunities for interventions.

Literature Review

The persistence and employment trends for Black women in STEM fields are critical areas of investigation, reflecting broader issues of diversity, equity, and inclusion in STEM education and careers (King, 2021). Prior research indicates that Black women face unique challenges at various stages of the STEM pipeline, from K-12 education to professional careers. This review synthesizes relevant literature on STEM participation and outcomes for Black women, providing context for the current study's exploration of STEM AP exam performance, college enrollment intentions, degree attainment, and employment trends.

Black Female Student Participation in K-12 STEM Education

The journey to STEM careers often begins with early exposure and success in STEM subjects during K-12 education. Research has consistently demonstrated that participation in Advanced Placement (AP) courses is strongly associated with higher rates of declaring a STEM major in college (Bohrnstedt et al., 2023; Maltese & Tai, 2011; Warne et al., 2019). Jewett and Chen (2020) found these effects to be even stronger for girls, with Chen et al. (2024) finding that taking high school computer science courses enhanced girls' chances of majoring in computer science related fields. These courses and exams serve as critical indicators of early engagement and preparation, offering students a challenging curriculum that can inspire continued interest in STEM fields. Moreover, success in AP STEM courses can allow students to earn college credit, which may further motivate them to pursue STEM degrees and careers.

Despite the recognized benefits of AP courses, Black female students are significantly underrepresented in STEM-related AP courses. A report by the College Board (2012) highlights that Black girls are enrolled in STEM AP courses at much lower rates than their White and Asian counterparts. This underrepresentation suggests systemic barriers that limit access to these rigorous courses, an under-representation mentioned frequently in the literature (Hirschl & Smith, 2023; Young et al., 2020). Factors affecting Black female participation and success in AP STEM courses include a lack of resources, insufficient preparation in earlier grades, and limited encouragement from teachers and counselors (Collins et al., 2020). This disparity in access can lead to fewer opportunities for Black girls to develop the foundational knowledge and skills necessary for success in STEM.

Furthermore, Black girls who show interest and potential in STEM often face additional challenges, such as a lack of mentorship and support. Studies have shown that mentorship fosters students' interest and persistence in STEM (Riegle-Crumb & King, 2010; Young et al., 2019). Without role models and mentors who can guide and encourage them, Black female students may struggle to see themselves succeeding in STEM fields, as suggested by literature finding that role model interventions can increase STEM aspirations (Gonzalez-Perez et al., 2020). This lack of support and limited access to rigorous coursework for Black girls can impede their progress through the STEM pipeline, ultimately affecting their enrollment and retention in post-secondary STEM education as shown by Ireland et al.'s (2018) review of the literature on Black women and girls in STEM education. Addressing these barriers is essential for increasing the participation and success of Black female students in STEM, thereby diversifying the field and enriching the STEM workforce.

Black Female Student STEM College Enrollment Intentions

College enrollment intentions are a proxy for interest in STEM careers and indicate future STEM participation. According to data from the Higher Education Research Institute (HERI), Black women are significantly less likely than their peers to express intentions to major in STEM fields (Eagan et al., 2016). This disparity reflects broader systemic issues, including the underrepresentation of Black women in STEM disciplines, which can discourage interest and confidence in pursuing these careers. The visibility of role models and mentors in STEM is crucial. Without seeing people who look like them succeeding in STEM, Black women may feel that STEM careers are not accessible or welcoming (Dickens et al., 2021). The cultural and social dynamics influencing career choices further compound this issue.

Black women often navigate complex intersections of race and gender, which can shape their educational and professional aspirations. Studies collected by a qualitative meta-synthesis have shown that societal expectations, family influence, and community support play significant roles in career decision-making (Jaumot-Pascual et al., 2021). The lack of culturally relevant curricula and supportive environments in educational institutions can also deter Black women from pursuing STEM majors (Espinosa, 2011; McGee, 2021). These barriers highlight the need for targeted initiatives that address the unique challenges faced by Black women, fostering an inclusive and encouraging atmosphere for their academic pursuits.

Black Female Student STEM Degree Attainment

The attainment of STEM degrees is a critical milestone in the STEM pipeline, serving as a gateway to advanced career opportunities and leadership roles within the STEM fields. Despite progress in overall STEM degree completion, significant disparities persist for Black women who only comprise 2% of the STEM workforce (Fletcher et al., 2023; Sendze, 2023). The National Science Foundation's (NSF) report on Women, Minorities, and Persons with Disabilities in Science and Engineering (2013) highlights these disparities, noting that Black women are particularly underrepresented among STEM degree recipients. This underrepresentation is most pronounced in high-demand fields such as engineering and physical sciences, where the presence of Black women is notably sparse compared to their peers (Charleston et al., 2014). Such trends underscore the importance of targeted interventions to support Black women through their educational journeys in STEM.

Several factors contribute to the underrepresentation of Black women in STEM degree retention and attainment. Academic preparation is a significant barrier, as many Black female students have limited access to advanced coursework and resources critical for success in STEM fields (Block et al., 2019). Financial barriers also play a crucial role, with many Black women facing challenges in affording higher education due to systemic economic disparities (Clotfelter et al., 2008; Shapiro, 2004). Additionally, the pervasive impact of stereotype threat—a phenomenon where individuals from marginalized groups experience anxiety and reduced performance due to negative stereotypes about their group's abilities—further hampers the academic success and persistence in STEM disciplines of Black women and girls (Burnett et al., 2023; Steele, 1997). These challenges are compounded by a lack of role models and mentors who can provide guidance and support through the rigors of STEM education. Both Dickens et al. (2021) and Ireland et al. (2018) emphasized the importance of mentors and support systems in retaining Black women in STEM fields. The systemic challenges Black women face in STEM education are not isolated to academic environments but extend into the workforce, where similar barriers impede their representation and career advancement in STEM professions.

STEM Employment Trends for Black Women

The transition from STEM education to employment presents significant challenges for Black women. According to data from the National Center for Science and Engineering Statistics (NCSES, 2023), Black women remain underrepresented in STEM occupations, especially in high-status fields such as engineering and computer science (Fletcher et al., 2023; Yamaguchi & Burge, 2019). This underrepresentation is not only a matter of lower participation rates but also reflects systemic barriers that hinder the career progression of Black women in STEM. These barriers include limited access to resources, mentorship, opportunities for advanced education, and exposure to high-level STEM projects and roles (Ireland et al., 2018). The cumulative effect of these obstacles is a persistent gap in the entry and retention of Black women in STEM professions.

Discrimination, both overt and subtle, is a significant barrier to the entry and advancement of Black women in STEM careers. Studies have documented instances of racial and gender bias that manifest in various forms, from hiring practices to workplace interactions and evaluations (Beasley & Fischer, 2012). Black women often lack mentorship and sponsorship, crucial for career development and progression. The absence of role models and mentors who share similar racial and gender identities can lead to feelings of isolation and discouragement. Moreover, according to McGee and Bentley (2017), networking opportunities, which are vital for career advancement, are frequently less accessible to Black women, further limiting their ability to progress in their careers.

The research presented in this literature review highlights the systemic barriers that Black women face at each stage of the STEM pipeline. These barriers include early educational experiences, college enrollment intentions, degree attainment, and employment outcomes. All of these reflect broader patterns of inequality that need to be addressed to create a more inclusive STEM ecosystem. The current study builds on this foundation by analyzing multiple data sources to provide a comprehensive overview of STEM persistence and employment trends for Black women. By highlighting these trends, the study aims to inform policy and practice interventions to support Black women navigating and succeeding in STEM fields.

The Opportunity-Propensity Framework

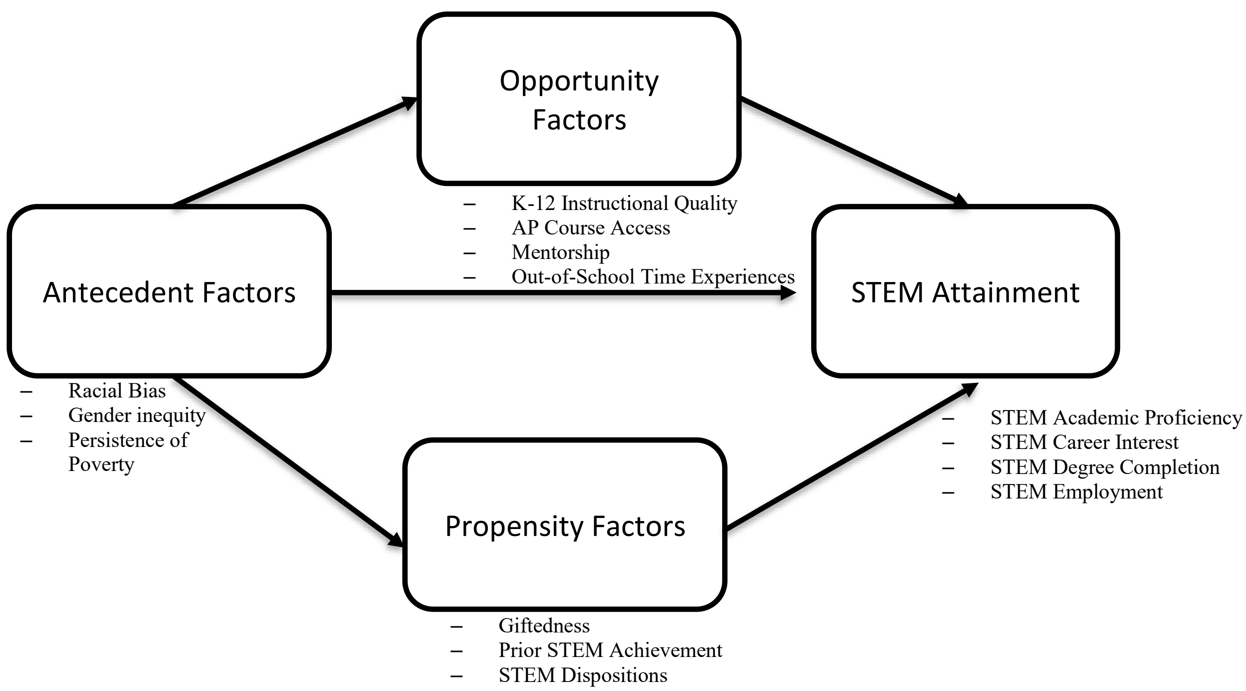
Numerous theories and frameworks explain the underachievement and lack of retention of Black women and girls throughout the STEM pipeline. According to Ford et al. (2011), relevant theories include: (a) Stereotype Threat, (b) Attitude-Achievement Paradox, (c) Secondary Resistance Among Involuntary Minority Groups, and (d) Acting White (see also Fordham & Ogbu, 1986; Mickelson, 1990; Ogbu, 1987; Steele, 1997). In the present study, we argue that opportunities to learn are the main hindrance to the achievement and retention of Black women and girls in STEM. These opportunities to learn are particularly inaccessible in STEM classrooms that serve both large populations of students of color and white students experiencing poverty (Basile & Lopez, 2015;

Heafner & Fitchett, 2015). The relationship between these opportunities and the success of Black women and girls in STEM is further explained by considering the Opportunity Propensity Framework in the context of critical transition points within the STEM pipeline, such as high school, college, and early career.

Opportunities to learn remain elusive for minoritized students of color and white students experiencing poverty. These opportunities are necessary to develop students' interests that promote participation and persistence in STEM-related content and careers. According to the opportunity-propensity framework, learning is influenced by three factors: (a) antecedent, (b) opportunity, and (c) propensity (Byrnes & Miller, 2007). Numerous studies indicate that antecedent factors (e.g., race, gender, and socioeconomic status) and opportunity factors (e.g., teacher quality and access to rigorous curricula) have an acute effect on the learning of traditionally minoritized learners. Still, propensity factors (e.g., giftedness, motivation, interest, and identity) also warrant further consideration (Young, 2020; Young et al., 2017, 2018). The opportunity-propensity framework provides a conceptual model of the interplay between these related factors and subsequent student learning. As shown in Figure 1, antecedent factors directly and indirectly influence STEM attainment. The impact of race and gender on the STEM attainment of Black women and girls is complicated by the effects of dual marginality, which is well-documented within the intersectional research literature, finding STEM interest and achievement to be critical themes (Ireland et al., 2018).

Figure 1

Operationalization of the Opportunity-Propensity Model for the Examination of Factors Related to the STEM Attainment of Black Women and Girls



Note: Adapted from Brynes and Miller (2007, p. 602).

Antecedent Factors and Dual Marginality

Black female learners are often unaccounted for in middle and high school advanced mathematics and science courses. During the 2015-2016 school year, Black girls accounted for 16% of high schoolers enrolled in STEM classes (U.S. Department of Education, 2018). Black girls who pursue and are successful in STEM fields are seen as an anomaly and are more susceptible to experiencing racism and gender-based exclusion. This trend is often attributed to the "double jeopardy" or additive discrimination Black female learners face as members of two stigmatized groups (King, 2016; Young et al., 2017). Black girls who persist through the STEM pipeline encounter various barriers (i.e., racism, sexism, academic, and systemic factors) that can inhibit their STEM attainment. Black girls and Black women are overlooked and, in many cases, entirely excluded from professional STEM careers.

Not only do Black women and Black girls face multiple intersecting marginalizations due to their racial and gender status, but they also combat academic and professional stereotypes based on decades of deficit-oriented scholarship built on the persistence of the Black-White achievement gap (Burnett et al., 2023). The gaps in performance between White and Black students are notable, but the magnitude of these gaps is extreme in mathematics and science, even within gifted education. For instance, White girls, regardless of gifted identification, statistically significantly outperform Black girls identified as gifted in both mathematics and science on the 4th grade National Assessment of Educational Progress (Young et al., 2017). This unfortunate finding can be attributed to the influence of antecedent factors on Black girl achievement within the Opportunity Propensity Framework.

Propensity Factors: Black girl STEM dispositions

The influence of antecedent factors does not operate in isolation; rather, antecedent factors are moderated by the effects of opportunity and propensity factors. For the present discussion, we focus on the influence of a specific propensity factor for Black girls: STEM dispositions. Black girls possess unique mathematics and science affinities and skills that can remain unrealized if not cultivated before middle school because data trends indicate girls lose confidence in their STEM abilities and experience a decrease in their STEM dispositions in the middle grades (Knezek, 2015). Surveys historically report more negative STEM dispositions among girls and women overall (Sadler et al., 2012; Wang & Degol, 2013). However, Black girls historically express more positive dispositions toward STEM content and professions than White girls (Charleston et al., 2014; Johnson, 2011).

Therefore, early STEM preparation for Black girls has the propensity to prime the STEM pipeline for Black girls. Harnessing the knowledge and skills of Black girls requires more intersectional research within STEM education. STEM career choices are influenced by inadequate STEM preparation early in the K-12 pipeline, arguably where the most substantial leaks can occur. This lack of preparation becomes more apparent in secondary and postsecondary course interest and performance (Decoito, 2014). Approximately 25% of Black students are interested in STEM but lack sufficient preparation in mathematics to pursue a STEM career (Business-Higher Education Forum, 2011). Student perceptions of their abilities and prior performance in mathematics and science mediate dispositions such as STEM interest and identity development (Hughes et al., 2013). Thus, as students become more aware of their inadequate preparation and proficiency, they are more likely to become disinterested in STEM. However, if Black girls are identified and placed in high-quality STEM education programs, their talents can be cultivated, which supports a positive STEM identity. Therefore, researchers must assess Black girls' mathematics and science achievement and dispositions early and often. Thus, access to equitable opportunities is an additional consideration modeled within the Opportunity Propensity Framework.

Opportunity Factors and Equitable Access to Advanced STEM Content

Several opportunity factors are important to consider when examining the STEM attainment of Black women and girls, such as teacher quality, enrichment activities, and technology resources. However, we will focus on access to and participation in STEM-related AP courses. Traditionally, AP courses are offered to the highest-achieving high school students to earn college credit before entering postsecondary educational settings (Klugman, 2013). Thus, participation and success on AP exams is an important indicator of STEM success for Black female high school students because they require content mastery, foster higher-order thinking, and are predictive of subsequent success in related content areas in college (Chajewski et al., 2011; Marin & Halpern, 2011). These courses are typically reserved for the top five to 10% of students and often require a teacher's recommendation to participate (Klopfenstein & Lively, 2016). Teacher recommendations and financial barriers can often impede the access of Black female students to AP STEM courses.

Because AP courses are arguably one of the most widespread and standardized resources for academically and intellectually gifted high school students, alongside International Baccalaureate and dual enrollment, we have placed our attention here, rather than earlier in the pipeline, where Black girl data is less representative (Park et al., 2014; Speroni, 2011). AP exams also permit using a single data source that provides disaggregated data by race and gender for all U.S. students rather than relying on a selected sample. Furthermore, because many of the same mechanisms and protocols are used to identify students for AP courses, there are implications for access, participation, and success that are applicable to STEM education. AP courses are extremely rigorous, and college credit is only granted to students who earn a specific score on the AP examination, typically a three or above. AP exam scores range from one to five. Still, according to the College Board, a score of five indicates that a student is exceptionally well qualified in that content area, and a score of one does not receive a recommendation.

Access, participation, and achievement in AP coursework remain a challenge for many minoritized students in the U.S. Even as AP enrollment and test taking have increased, racial and socioeconomic gaps in course-taking and scores remain (Rodriguez & McGuire, 2019; Xu et al., 2021). In 2013, Black students represented 14.5 percent of the graduating student population, 9.2 percent of the AP exam participants, and only 4.6 percent of the students earning a three or above on an AP exam, the score typically needed to receive college credit (College Board, 2014). Unfortunately, although participation has increased for Black students over the last few decades, performance trends have not. Black student pass rates declined from 35.9 percent in 1997, to 29.1 percent in 2012 (Eugene & Hobson, 2015). Additionally, results of the 2016 exam indicate that over 70 percent of Black students who took an AP exam did not pass, indicating that this decline has remained consistent (Tugend, 2017). For girls, these numbers can be even worse, with Krakehl and Kelly (2021) reporting traditionally underrepresented women had failure rates of over 80% on the AP Physics 1 exam. By examining antecedent, propensity, and opportunity trends, the Opportunity Propensity Framework provides a theoretical lens through which we can characterize the Black female data trends along the STEM pipeline.

Method

This study uses multiple data sources to characterize the STEM attainment trends for Black women and girls across four crucial points in the STEM pipeline. Altogether, we summarized and analyzed four main sources of data: STEM AP exam performance, STEM college enrollment intentions, STEM college degrees, and STEM employment. These data help unpack a complex narrative of systemic barriers and resilience, highlighting persistent inequities and opportunities for targeted interventions to support Black women and girls in STEM.

Data

We used the reporting data (i.e., means and standard deviations) for Black girl performance on the 2012 administrations of the STEM-related AP exams from the College Board to answer our first research question: How is the STEM preparation of Black girls characterized by Advanced Placement (AP) exam participation and performance? To answer this question, we extracted data for STEM-related AP exams. We chose the following AP exams as relevant STEM content: Biology, Chemistry, Environmental Science, Calculus AB, Calculus BC, Statistics, Computer Science, Physics B, and Physics C1. Data were analyzed from *N* = 32,675, for every Black female learner in grades 9 through 12 who took the AP exams. We received the data directly from the College Board, which creates and administers the exams. These data represent the early STEM content participation and preparation of arguably the highest-achieving Black girls in the nation. As these datasets contained descriptive statistics (i.e., *N*, *M,* and *SD*), we calculated 95% confidence intervals for data inference. We present confidence intervals in visual form via graphs and include the proportions of each test taken by Black girls in 2012 as a pie chart.

Next, we analyzed data from the NSF's Women, Minorities, and Persons with Disabilities in Science and Engineering 2013 report. This data provided information about STEM-related degrees earned by Black women. The included fields are mathematics and statistics, engineering, biological sciences, physical sciences, and computer science. Computer science and information technology are often grouped in the same category regarding degrees, as an undergraduate computer science degree is frequently used as a prerequisite for entry into IT jobs (Charles & Bradley, 2006). Data were analyzed for a sample *N* = 1,159,157 of Black female college graduates. This data comes from surveys administered by federal organizations: NCSES, National Center for Education Statistics, Department of Education, Census Bureau, Department of Commerce, and Bureau of Labor Statistics. These data were summarized using descriptive statistics (i.e., frequencies) displayed as a line graph over time.

Finally, we summarize employment trends from the data from the NCSES 2015. The fields of employment included mathematical scientists, physical scientists, psychologists, social scientists, engineering positions, biological and life scientists, and computer and information scientists. While psychologists and social scientists were included based on their designation by the NSF, we will not be discussing those results as they do not match the study's definition of STEM. Data were analyzed for a sample *N* = 116,388 Black female college graduates. These data were summarized using descriptive statistics displayed as a pie chart.

Analysis

In the sections that follow, we provide single-group summaries of Black female performance at critical points in the STEM pipeline to explore participation and achievement trends across the STEM pipeline. Researchers in the medical sciences utilize single-group summaries to explicate the unique medical considerations of different demographic groups (Blank & Antaki, 2017; Najafi et al., 2015). A single-group summary is the estimation of group trends for specific populations or categories of participants on a particular outcome (e.g., the prevalence of disease amongst women or mean score for children experiencing poverty on a test). Here, we utilize single-group summaries to characterize data related to STEM learning outcomes for Black women and girls. Confidence intervals were selected because they provide point estimates for population parameters, as well as a measure of the precision of these estimates that were used to compare across administrations (Cumming & Finch, 2001). The point estimates are sample statistics, two of the most commonly used: means and effect sizes (Zientek et al., 2010). The sample statistics were referred to as point estimates because they approximate population parameters. Using confidence intervals to compare and characterize Black girl AP STEM performance is critical because it allows for a more nuanced understanding of differences and trends that simple point estimates might otherwise mask. Confidence intervals offer a visual and statistical way to assess the overlap and distinction between group performances, helping to identify both meaningful gaps and areas of progress. This approach strengthens the validity of inferences drawn about population-level achievement patterns, ensuring that interpretations are both statistically grounded and sensitive to the variability inherent in educational data.

The present study used a sample of African American female mean scores on each exam as point estimates. A 95% confidence interval was chosen by convention; a 90% or any other level would be equally valid, but the 95% confidence interval is a stricter measure (Zientek et al., 2010). A 95% confidence interval does not indicate that a point estimate correctly represents the population parameter with 95% certainty, but rather that if an infinite number of confidence intervals are constructed, then one can be 95% certain that the population parameter is present. The confidence intervals were calculated in Microsoft Excel, specifically the confidence macro present in the available list of macros. To perform these calculations, one needs the mean, standard deviation, and population size retrieved from the College Board.

Results

Black women and girls have the potential to become strong leaders in STEM, lending their unique expertise to improving the STEM field. Specifically, Black girls represent a unique population of K-12 learners who remain an essentially untapped sources of STEM potential. The results in the sections below provide important implications for education praxis to support Black girls and women at critical moments in the STEM education pipeline.

AP Participation and Performance

Based on the descriptive statistics summarized in Table 1, the mean scores across five science subjects (i.e., Biology, Chemistry, Environmental Science, Computer Science, and Physics B) were below the minimum passing score of three or better on the AP exam.

Table 1

Descriptive Statistics of AP Exam Scores Across Science and Mathematics Tests for Black Girls

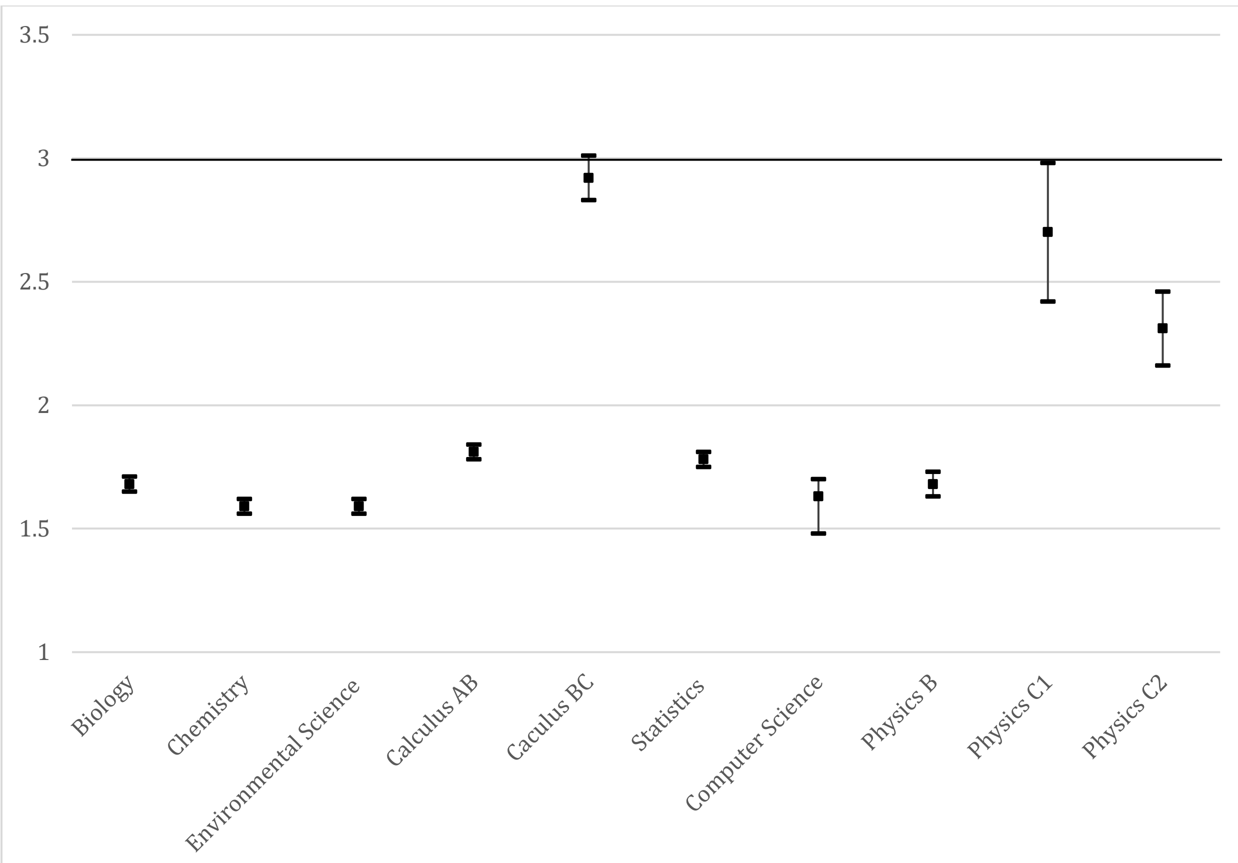
Science							
	Biology	Chemistry	Environment	Computer Science	Physics B	Physics C_1	Physics C_2
N	8210	3876	4347	252	1571	89	270
M(SD)	1.68(1.17)	1.59(1.03)	1.67(1.02)	1.63(1.24)	1.68(1.00)	2.70(1.34)	2.31(1.28)
Mathematics							
	Calc AB	Calc BC	Statistics	Calc AB	Calc AB	Calc BC	Statistics
N	7791	1026	5243	7791	7791	1026	5243
M(SD)	1.81(1.27)	2.92(1.52)	1.78(1.05)	1.81(1.27)	1.81(1.27)	2.92(1.52)	1.78(1.05)

Note. 1= Electricity and Magnetism; 2= Mechanics; CI= 95% confidence interval for the mean

Mean mathematics performance across three math subjects (i.e., Calculus AB, Calculus BC, and Statistics) followed a similar trend. Mean scores on the Calculus AB and Statistics exams were less than the mean score of three necessary to receive college credit at most colleges and universities. The mean scores on the Calculus BC exam were only 0.08 of a point away from the score needed to earn college credit. This indicates that the overall performance of Black girls on this exam was close to a score of 3.0, which would be a sufficient score to earn college credit for Calculus 1 and 2. Few Black girls earned college credit from any STEM AP courses based on the mean group performance. This is further evidenced by the data in Figure 2, which presents the 95% confidence interval plots for the mean performance of Black girls across STEM content areas.

Figure 2

95% Confidence Intervals for Mean Scale Scores of Black girls on AP STEM

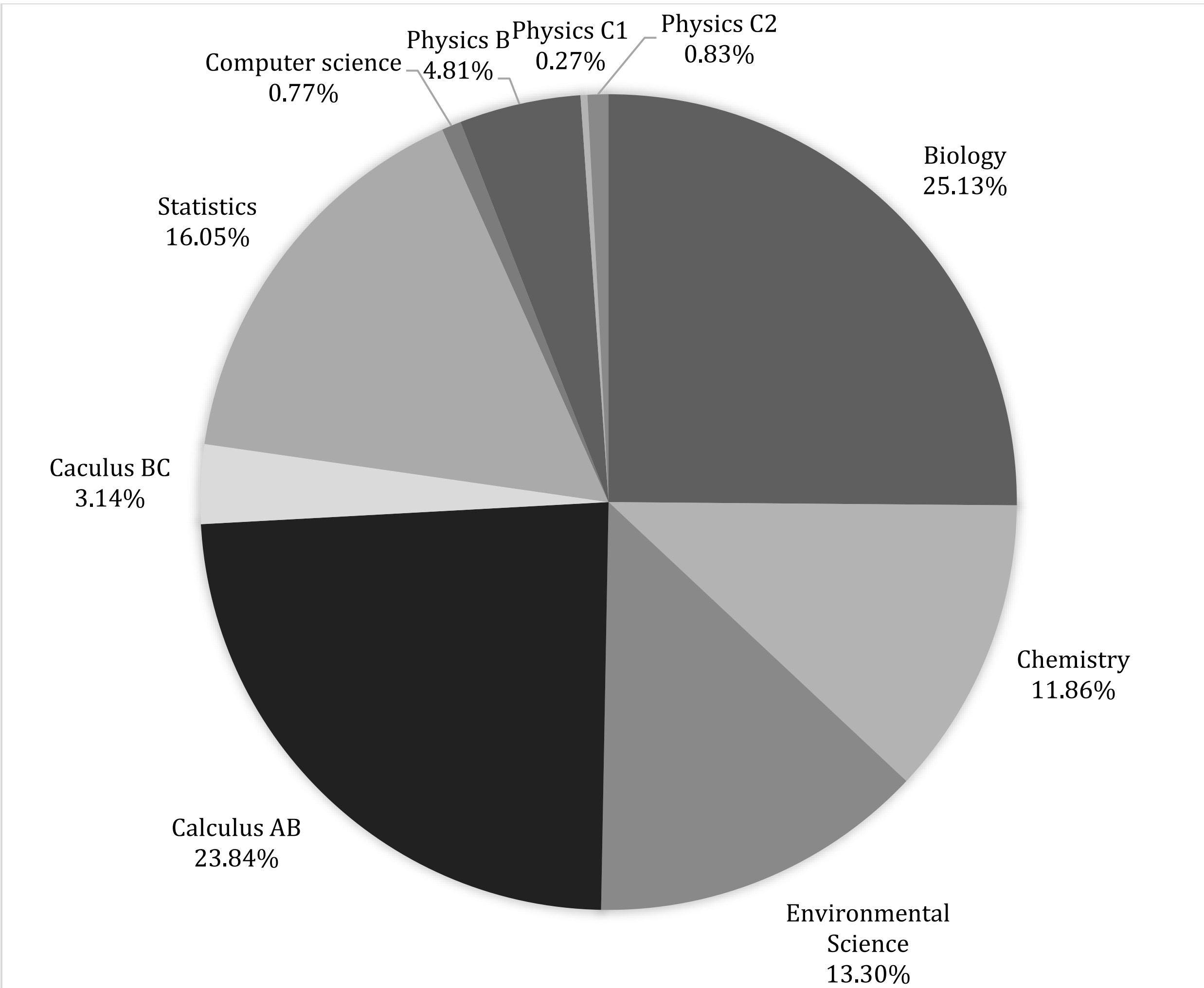


The dots represent the mean score, while the bands extending from the dots represent the 95% confidence interval range. Based on the lack of overlap between the confidence bands of the content areas and the score of three, as depicted by the bold black line in the figure, it can be concluded that most Black girls do not earn college credit through AP examinations.

Figure 3 represents the proportion of each test in our sample of Black girl AP test takers. Representation data presented in Figure 3 indicate that the largest proportion of Black girls in our sample attempted the Biology and Calculus AB exams, respectively. Fewer than 10% of Black girls attempted the Calculus BC, Computer Science, and Physics exams combined. This is interesting because score trends for these exams were typically slightly higher than the mean scores for the attempted exams more often. This may indicate rigor, access, and instructional quality differences across the STEM examinations. However, as mentioned earlier, schools serving large populations of Black students tend to have fewer AP exam options. Hence, it could be argued that the higher scores for Black girls on the more rigorous AP exams reflect the effects of increased access and opportunities to learn at schools serving primarily White students. Yet, the absence of these variables within this dataset made it impossible to investigate this further.

Figure 3

Black Female Student AP STEM Exam Participation

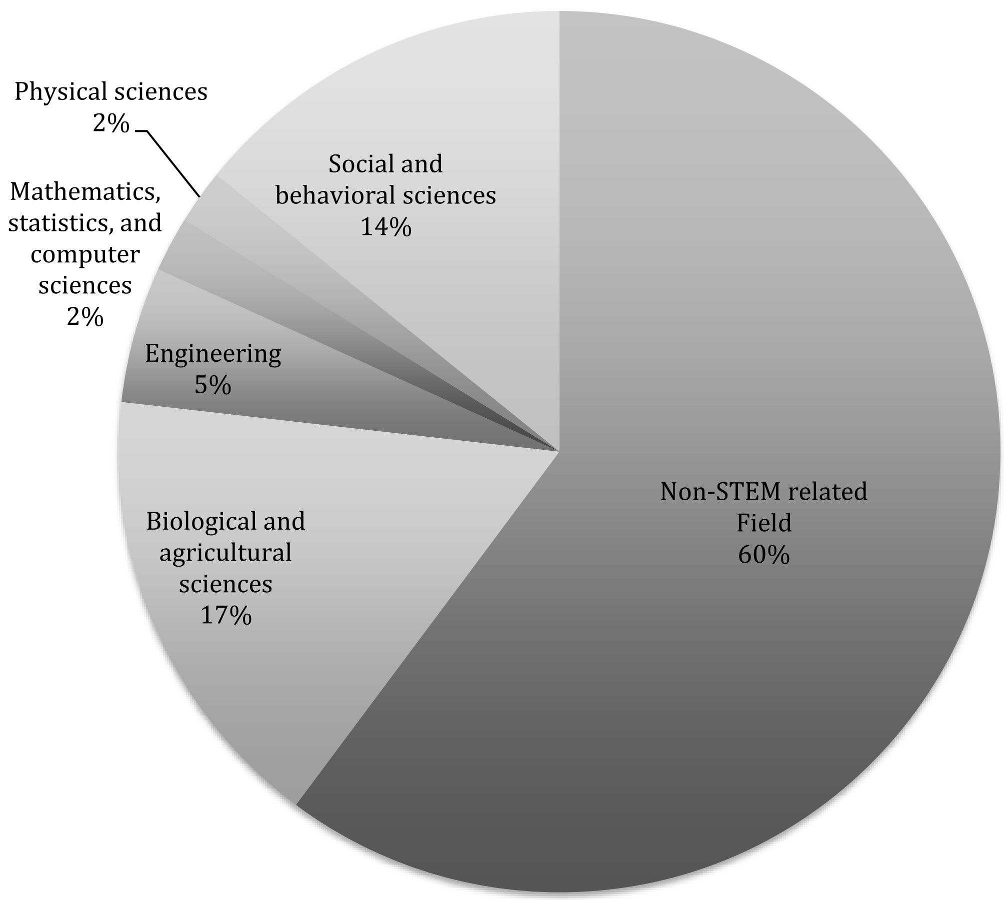


Enrollment Intentions

According to the data summarized in Figure 4, those who intend to pursue a STEM-related field are more likely to consider a biological and agricultural sciences major than more computational sciences. The data in Figure 4 also indicates that only approximately nine percent of Black female freshman students intend to pursue physical science, mathematics, engineering, or computer science. These represent what some would consider more computationally heavy STEM content areas. A similar trend is present within the AP participation and performance data presented in the previous section, where the largest proportion of Black girl test takers took the Biology AP exam at 25%. Notably, enrollment intentions favor biological sciences, which is comparable to the vast number of Black female students attempting the biology AP exam.

Figure 4

Black Female Student Freshman Enrollment Intentions



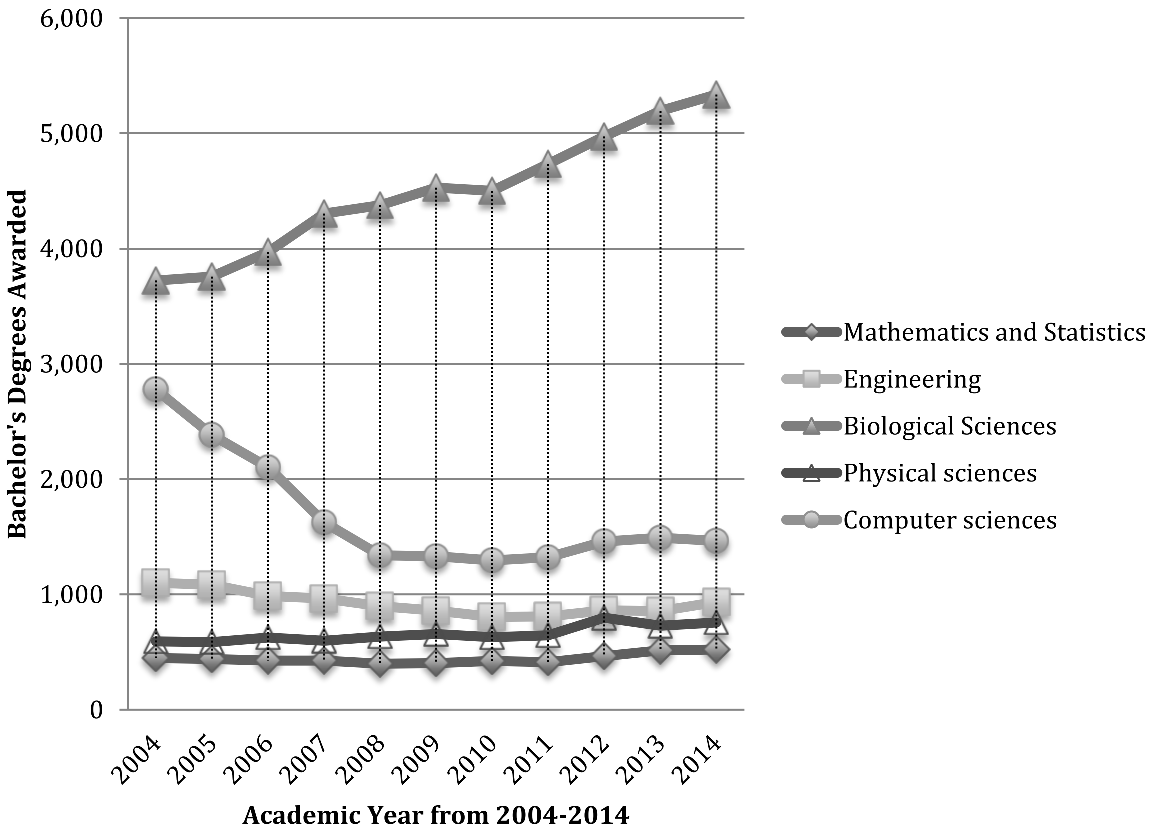
STEM career interest begins early, but we can learn a great deal from reviewing the enrollment intentions of Black female students based on major course of study declarations. As presented above, data from the Higher Education Research Institute's 2014 survey of American freshmen indicates that most Black female freshman college students do not intend to earn a degree in a STEM-related field. This finding parallels the historical trends in STEM career interest for Black female students and female learners in general.

Degree Attainment

According to data from the NSF, between 2004 and 2014, most Black female STEM learners earned a degree in biological sciences. This was the only STEM-related field with a positive degree attainment trend. This result coincides with the trends in Black female student enrollment intentions and the most attempted AP exams. The complete set of degree attainment trends can be seen in Figure 5.

Figure 5

Black Female STEM Degree Attainment Trends from 2004 to 2014



Computer science degree attainment experienced a sharp decline from 2004 to 2008 and has been relatively flat since 2009, while engineering, physical sciences, and mathematics/statistics historically represent the three lowest degree attainment career categories for Black girls. Likewise, these areas also represent three of the least attempted AP exams for Black girls, with some subtle nuances related to AP exam performance in each content area. As Nix and Perez-Felkner (2019) observed, Black women who believed they had a higher ability to handle difficult mathematical tasks were more likely to have outcomes in physics, engineering, mathematics, and computer science. This could connect with those willing to take the potentially difficult related AP exams.

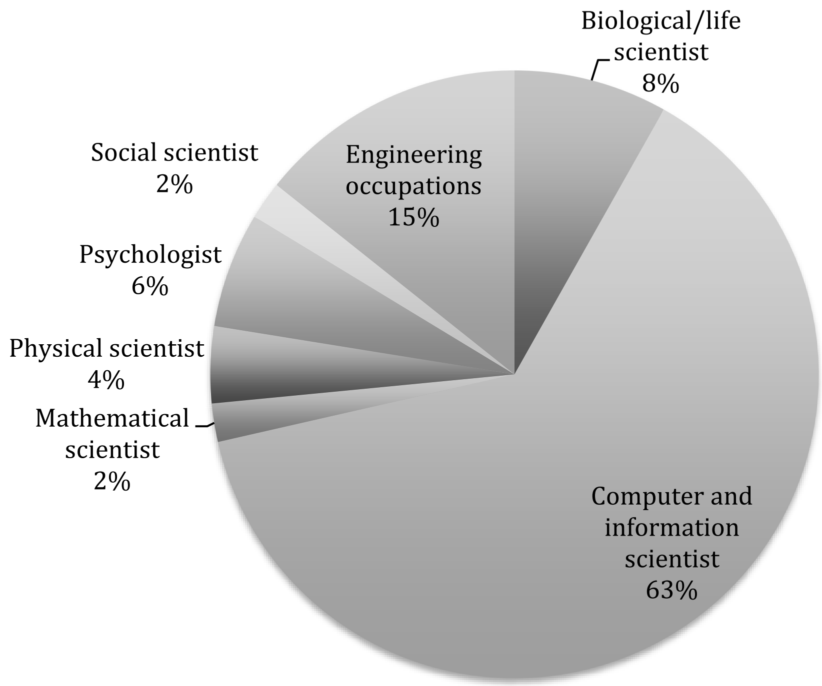
Employment Trends

According to the NCSES 2015 survey of college graduates, most Black female STEM professionals with a bachelor's degree are often employed as computer or information scientists. This suggests that although fewer Black female students are attempting AP computer science, enrolling in computer science as a major, or graduating in computer science-related fields, computer-related careers remain the largest STEM profession for Black female professionals with a bachelor's degree. Similarly, the second largest proportion of Black STEM professionals are employed in engineering fields despite very low intent to major in engineering for Black girls. A final point for consideration is the disconnect between substantial Black girl participation and performance challenges in the Biology

AP exam compared to the large number of degrees earned in the biological sciences and the relatively small number of Black women employed in related fields.

Figure 6

Black Female Professional STEM Employment Distribution



Limitations

Our data allows us to examine general trends for Black women and girls in STEM and make inferences about their path. However, as this is aggregate data, we cannot control for factors such as socioeconomic status and self-efficacy. Also, the categorization options in the dataset limit the information available about specific STEM fields entered. For example, while biological/life scientists could include various life science-related fields, we cannot see that in the data. Additionally, we focused solely on STEM careers, yet it is reasonable to assume that Black women in the sample went on to successful non-STEM careers in business or other fields. Furthermore, we cannot truly determine the causes behind this trend and can only hypothesize based on previous research. It would be remiss not to mention that these data do not include Black women with advanced degrees, nor are the exact numbers of Black girls identified as gifted provided in national datasets. Here, we only use AP data, while some scholars have considered dual enrollment courses where high school students earn college credit to be an evenly matched alternative to AP coursework.

Discussion

Reports repeatedly conclude that Black women and girls are uniquely resilient, creative, and productive STEM learners (Farinde & Lewis, 2012; Young et al., 2017). The findings of this study highlight critical trends and challenges in the STEM pipeline for Black women and girls, offering valuable insights into their educational and professional trajectories. The discussion integrates these findings into a cohesive narrative, focusing on the relationship between preparation, degree attainment, and career outcomes while aligning with the Opportunity Propensity Framework to contextualize the results.

AP Participation and Performance

Black girls' STEM preparation through AP exam participation and performance is characterized by underrepresentation in more advanced exams and lower-than-passing mean scores in most STEM subjects. For instance, few Black girls earned college credit from STEM AP exams, as evidenced by the lack of overlap between the 95% confidence intervals for mean performance and the passing score of three. This highlights the challenges Black girls face in achieving college-credit-qualifying scores on STEM AP exams. These results indicate limited access to resources and opportunities necessary for success on these exams.

The analysis revealed significant disparities in AP participation and performance among Black girls, particularly in computationally intensive subjects such as computer science and advanced mathematics. However, prior research indicates that large populations of students of color lack opportunities to participate in high school advanced mathematics and science courses (Woolley et al., 2010). These gaps are consistent with broader inequities in STEM education access. Some posit that underrepresentation results from cultural discontinuity or mismatch between teachers and Black girls (Ford, 2013; Young & Larke, 2017). Cultural discontinuity is one mechanism that dually marginalizes Black girls in gifted education and STEM education. These findings underscore the interplay between systemic inequities in educational access and the untapped potential of Black girls in STEM, highlighting both the challenges and opportunities for intervention.

The higher mean scores on Physics C exams suggest that, when opportunities align with strong preparation and support, Black girls can succeed in even the most challenging STEM subjects. The implications of these findings are profound. Limited participation in AP courses restricts the STEM opportunities available to Black girls at the postsecondary level, perpetuating a cycle of underrepresentation. While the trends in Physics C scores are promising, they highlight the importance of targeted resources and interventions to extend such success to other STEM subjects. Moreover, based on the results of the present study, we support the recommendation of the National Research Council (2013) to include factors beyond academic achievement when assessing the STEM academic capacity of Black girls.

Teacher training is integral to creating more equitable STEM opportunities by gender, race, or both because when a student's giftedness deviates from the teacher's perceived norm, the student may not receive a referral, even when matched on test scores and grades with White students (Ford & Moore, 2013; Grissom & Redding, 2016). Thus, we recommend specialized STEM identification training for AP courses to help address the underrepresentation of Black girls in AP STEM courses. The number of states that require pre-service teacher training in gifted education is limited (Farkas & Duffett, 2008), especially with a multicultural focus (Ford, 2011a). Only 17 states require teachers to have gifted education credentials (see National Association for Gifted Children, 2014).

Teacher perceptions are informed by cultural synchronization, or the ability of teachers to recognize and appreciate the cultural nuances and characteristics of culturally and linguistically diverse students (Mattai et al., 2010). When cultural synchronization exists, the possibility of misinterpretations of cultural orientations is decreased. Thus, training teachers who serve culturally, linguistically, and economically diverse students on how to recognize high ability, as well as how to respond, is imperative (Ford, 2011b; MacFarlane, 2015). However, as observed in the AP data from the present study, this training must be content-specific and reflective of trends in access, participation, and performance.

Regarding early preparation and AP performance, the present study's results indicate that Black girls' participation in AP STEM exams is low, particularly in computationally intensive subjects like computer science and advanced mathematics. Moreover, when Black girls do participate, their scores often fall below the threshold for college credit, reflecting disparities in preparation. Yet, promising data trends in Physics C scores demonstrate that with proper preparation and support, Black girls can excel in challenging STEM areas, underscoring the importance of targeted resources and interventions.

College Enrollment Intentions

The predominant professional intentions in STEM fields among Black women at the onset of their college education are concentrated in biological and agricultural sciences rather than computationally intensive areas such as physical sciences, mathematics, engineering, or computer science. According to the data, only about 9% of Black female freshman students intend to pursue degrees in these computational STEM areas. This trend aligns with AP participation data, showing that the most significant proportion of Black female AP test takers took the biology exam (25%), indicating a stronger preference for biological sciences.

Additionally, historical trends suggest that most Black female students do not intend to earn degrees in STEM-related fields, a pattern reflective of broader trends in female learners' STEM career interests. Other studies have also found that women and girls are more drawn to biological sciences. Perez-Felkner et al. (2017) found that high school mathematics ability beliefs and performance made them more likely to major in physical science, engineering, mathematics, and computer science.

The results of the present study indicate that the same gender bias and institutionalized sexism within K-12 and higher education settings are also present in our nation's STEM culture (Moss-Racusin et al., 2015). However, it is essential to note that underrepresentation in high-demand fields like computer science and engineering reflects broader systemic barriers, including a lack of mentorship and culturally relevant curricula that might encourage broader STEM engagement. These enrollment intentions underscore the need for early interventions to diversify Black girls' STEM interests, addressing the cultural and structural factors that shape their academic and professional choices.

In sum, Black girls disproportionately intend to pursue biological sciences, with limited interest in computational and physical sciences. This trend reflects broader systemic and cultural influences, including a lack of mentorship and exposure to diverse STEM careers. We contend that gender biases and institutionalized sexism contribute to limited engagement in computational STEM fields, reinforcing traditional stereotypes about "appropriate" roles for women in STEM.

Degree Attainment

The longitudinal trends in STEM degree attainment among Black women over the past decade reveal significant disparities across STEM fields. From 2004 to 2014, biological sciences demonstrated the only positive trend in degree attainment for Black women, aligning with their enrollment intentions and the largest number of attempted AP exams. In contrast, computer science experienced a sharp decline in degree attainment from 2004 to 2008, stabilizing at a low level after 2009. Engineering, physical sciences, and mathematics/statistics consistently represented the lowest degree attainment categories, correlating with the minimal attempts at AP exams in these subjects.

These trends highlight a strong connection between perceived ability, willingness to engage with challenging content (e.g., AP exams), and outcomes in physics, engineering, mathematics, and computer science. As Nix and Perez-Felkner (2019) suggest, the belief in one's mathematical ability plays a critical role in degree attainment in these traditionally underrepresented fields. These findings underscore the need for targeted interventions to bolster confidence and preparation in these areas to support greater representation of Black women across all STEM disciplines.

Earlier data have suggested that the representation of women and Black women decreases with each advanced degree designation (Ceci et al., 2009). Thus, student achievement in STEM should be recognized and rewarded to foster future interest and efficacy in STEM (Beier & Rittmayer, 2008) to support advanced degree attainment. Addressing these gaps requires a dual focus on increasing access to advanced STEM coursework and fostering a sense of belonging in underrepresented STEM fields. Mentorship, role models, and supportive institutional cultures are critical for bridging this divide (Ireland et al., 2018).

Thus, the degree attainment trends indicate a multitude of disparities, with biological sciences being the only area of growth for Black women. In contrast, engineering, mathematics, and computer science remain critically underrepresented. Based on these trends, we argue that confidence in mathematical ability and access to challenging coursework are pivotal for the degree attainment of Black women. This highlights the need for interventions that build self-efficacy and engagement in underrepresented fields.

Employment Trends

Based on the employment distribution data, the representation of Black women across various STEM professions reveals distinct trends. Black women with bachelor's degrees in STEM are most frequently employed in computer or information science professions, despite their underrepresentation in AP Computer Science participation and degree attainment. Engineering fields represent the second-largest employment category for Black women in STEM, although the intent to pursue engineering among Black girls is notably low. Interestingly, there is a disconnect in the biological sciences. Despite substantial participation in biology AP exams and numerous degrees earned in the biological sciences, relatively few Black women are employed in these fields. This distribution highlights a misalignment between educational pathways and workforce representation for Black women in STEM.

The employment data reveal a disconnect between degree trends and workforce representation. Despite low degree attainment in computer science, Black women with STEM degrees are predominantly employed in computer and information science fields. This may reflect a combination of career adaptability and opportunities in less mathematically intensive roles within the technology sector.

These findings suggest the importance of aligning educational preparation with workforce demands. Unfortunately, people of color have been excluded from education advocacy discussions and advisory groups (Davis, 2010), which can contribute to Black women's lack of participation in certain STEM fields. This is important because representation affects the social, emotional, and racial identity development of students of color (Davis & Moore, 2016; Ford, 2010). For instance, cultural stereotypes are abundant, and these perceptions often lead many women to believe that STEM careers are not conducive to their desire to work with others (Diekman et al., 2011).

Strengthening pathways into high-demand STEM fields, particularly through internships and professional mentorship programs, could better prepare Black women for success in these careers. With respect to employment trends, the data indicate a workforce misalignment for Black women in STEM, as employment trends reveal a disconnect between educational preparation and workforce representation. Despite low degree attainment in computer science, Black women are more likely to be employed in technology sectors, reflecting adaptability and a misalignment between education and industry demands. Furthermore, despite high AP participation and degree attainment, the biological sciences see lower workforce representation, suggesting systemic barriers in translating education into employment.

Theoretical Implications

The following discussion situates the present study's findings within the opportunity-propensity theoretical framework, emphasizing how systemic barriers, intersecting identities, and cultural perceptions shape Black women and girls' educational and career trajectories in STEM. Although the racial achievement or opportunity gap may contribute to the lack of recruitment of Black girls into STEM careers, other data suggest that Black girls possess a unique affinity for STEM-related tasks despite divergent achievement trends (Hanson, 2004; Riegle-Crumb et al., 2011; Young, 2016a). Many gifted and academically advanced Black girls receive less than adequate STEM instruction because of a lack of learning opportunities and access to gifted education (Ford, 2014; Young, 2016b). Therefore, many Black girls are likelier to exhibit a strong interest in STEM but lack sufficient advanced preparation in mathematics and science.

The Opportunity Propensity Framework provides a valuable lens for interpreting these findings. Antecedent factors, such as race and gender, intersect with opportunity factors, including access to AP coursework and high-quality instruction, to shape Black girls' STEM trajectories. Propensity factors, such as STEM dispositions and self-efficacy, further mediate these outcomes. By addressing gaps in opportunity and fostering positive STEM identities, stakeholders can create conditions for success.

The Opportunity Propensity Framework aims to comprehend the impact of opportunities, individual propensities, and their interactions on educational outcomes. The results of the present study reveal several important implications for supporting Black girls and women in STEM education and professions. At the same time, it is crucial to consider how the opportunity-propensity theoretical framework may shed light on how systemic barriers and intersecting identities shape educational and career trajectories for Black girls and women in STEM.

Opportunity Implications

The resilience, creativity, and productivity of Black women and girls as STEM learners have been repeatedly highlighted in the STEM literature (Farinde & Lewis, 2012; Young et al., 2017). Despite this, the potential of Black women as leaders in STEM remains underutilized, especially among gifted Black girls in K-12 education. Our analysis of AP participation and performance reveals significant barriers.

The AP participation and performance trends indicate that many Black girls nationwide lack preparation in advanced science and mathematics content. The mean scores across five science subjects (Biology, Chemistry, Environmental Science, Computer Science, and Physics B) are below the passing score of three, with most mean scores under two. However, Physics C exams (Electricity and Magnetism and Mechanics) show promising results, with mean scores below three. This suggests that with better support and resources (i.e., opportunities), Black girls could achieve higher scores across all STEM subjects. However, small subsets of Black female learners seem well prepared in the most advanced mathematics and science content areas assessed on the AP exam.

This high-performing group of Black female learners is vital because persistence in STEM is highly contingent upon student achievement in the related mathematics and science content. Still, passion and support along the STEM pipeline are essential factors that cannot be overlooked. Ong et al. (2011) also noted, in a synthesis of the research, that difficulty with transition periods and discrimination discourage women of color from entering STEM fields. Currently, access to rigorous AP courses is limited for many Black female learners, particularly in schools serving large Black student populations, highlighting a critical need for equitable resource distribution.

Propensity Implications

Despite the challenges, black girls have shown potential in specific areas of STEM. The results of the Physics C exams indicate that when provided with the right opportunities, black girls can excel even in the most challenging subjects. This suggests an inherent propensity for success that could be harnessed with adequate preparation and support. Furthermore, enrollment intentions reflect a strong interest in biological and agricultural sciences, aligning with trends in AP exam participation, where Biology was the most attempted exam. Likewise, from 2004 to 2014, black women earned substantially more degrees in the biological sciences compared to other fields. More specifically, fewer than 10% of black girls combined pursue degrees in physical sciences, mathematics, engineering, or computer science.

On the other hand, longitudinal career data indicate that computer science declined from 2004 to 2008 before leveling off just above the bottom three categories. It is important to note that nationally, a concerted effort exists to increase women's presence in computer science. This is marked by national and university initiatives such as Black Girls Code, Code First: Girls, and Girls Teaching Girls to Code, to name a few (see Miller, 2013). These and other efforts to strengthen the recruitment and retention of women and underrepresented minorities in STEM fields have failed to foster racial and gender parity in the engineering, computer science, and physics disciplines, especially at the highest levels (Hill et al., 2010; Wang & I, 2016). The data presented in the present study indicate small increases and decreases observed in engineering, physical science, and mathematics/statistics from 2004 to 2014. However, Black girls earn substantially fewer STEM degrees in these areas. Thus, encouraging broader STEM interests from an early age could diversify the career paths of Black women and tap into their full potential as STEM professionals.

Antecedent Implications

The antecedent factors contributing to the current state of Black girls in STEM include systemic inequities in education and a lack of early exposure to a diverse range of STEM fields. Historical trends show that Black female freshmen are less likely to declare STEM majors, a pattern consistent with broader female student populations. Degree attainment data from the NSF between 2004 and 2014 show that biological sciences are the only STEM field with a positive trend among Black women. One consideration for the present study's employment trends is that women tend to feel out of place in most STEM fields (Stout et al., 2011). Thus, women and girls with the highest STEM interest and competence often choose STEM professions with the largest female representation (Perez-Felkner et al., 2012).

The trends from these data indicate that there is a substantial lack of correspondence between high school achievement, college enrollment intentions, degree attainment, and employment of Black women in STEM. For example, the small proportion of AP Computer Science test takers and freshmen intending to major in computer science, and the decline in computer science degree attainment, do not match computer and information science, which is the largest STEM employment field for Black women. This could be because information science is less mathematically intense and requires different skills than mathematically intense computer science and coding-related degrees.

Moreover, Black women who persist in the more coding-heavy computer science fields face multiple challenges that may not be present in information science (Thomas et al., 2018; Yamaguchi & Burge, 2019). Also, biology-related degrees could serve as a starting point for entering medical fields like nursing and medicine, which may explain the lack of biological scientists. However, such speculations are beyond the scope of this study. These disconnects warrant further consideration in the research literature. Fields like computer science, engineering, and physical sciences have low degree attainment rates. This is reflected in AP exam participation, where fewer Black girls attempt exams in these subjects. Addressing these antecedents requires initiatives that provide early and sustained exposure to a wide range of STEM disciplines, supported by mentors and role models who reflect their experiences.

Achievement Implications

Despite these barriers, Black women achieve notable success in STEM professions. Data from the NCSES (2015) show that most Black female STEM professionals with bachelor's degrees work as computer or information scientists, even though few pursue these degrees initially. This suggests that once in the workforce, Black women may gravitate toward less mathematically intense fields within STEM or face challenges in more coding-intensive roles. Similarly, many Black STEM professionals are employed in engineering despite low initial interest. There is also a notable disconnect between the high participation in Biology AP exams, degree attainment in biological sciences, and relatively low employment in related fields. This indicates a need for better alignment between education and career opportunities.

By addressing these issues, the untapped potential of Black girls and women in STEM can be fully realized, fostering greater diversity and leadership. The results of the early enrollment intention data were not surprising. Despite early STEM career interest, young Black women face unique obstacles in STEM, as noted earlier. Teacher bias and poor institutional support for pursuing STEM compound the double bind challenge for Black girls (Hill et al., 2010). This trend is similar to the results of Bowen et al. (2005), which concluded that students of color typically choose majors based on the ability to give back instead of potential monetary gain, with McGee and Bentley (2017) observing this among high-achieving undergraduate Black and Latinx STEM students. It is thus not unexpected that Black female students demonstrate a greater propensity to pursue disciplines such as biology or anatomy, given that these fields are intimately associated with professions such as medicine, where they are more likely to encounter role models who are Black women.

Conclusion

Black girls are an underrepresented resource for increasing and sustaining a diverse STEM profession. Increasing access and equity in STEM is a national concern referred to as the STEM crisis (Nasereddin et al., 2014). The U.S. Census Bureau (2012) posits that by 2050, one-half of the U.S. population will be non-White. Moreover, the absence of female professionals, particularly women of color, in STEM fields is a persistent problem (National Academy of Sciences, National Academy of Engineering, Institute of Medicine, & National Research Council, 2010). Despite the prevalence of this phenomenon, effective solutions remain elusive. There are widespread disparities in Black women's recruitment and retention in STEM (Young et al., 2017). Data indicate that Black women earn 10.7% of STEM bachelor's degrees and 13% of STEM master's degrees, yet comprise less than 1% of the STEM workforce (NSF, 2013).

Moreover, Black women's mathematics degree attainment is 800% less than that of white women (Pepitone, 2013). The ramifications of these data are twofold: (1) first, these data indicate that Black women are earning degrees in STEM but failing to matriculate into corresponding STEM professions at the same rate, and (2) these data indicate that Black women's STEM degree attainment and career success could be relegated to specific STEM content areas and professions. This significantly affects Black girls' STEM career interests and degree attainment. Despite these challenges, Black women pursuing STEM majors and careers often demonstrate remarkable resilience and determination (Sendze, 2023). Their commitment to overcoming obstacles and succeeding in STEM underscores the importance of providing robust support systems to sustain their interest and engagement. This includes mentorship programs, scholarships, and academic resources tailored to their needs (Ireland et al., 2018). Educational institutions and policymakers must prioritize these interventions to ensure Black women enter and thrive in STEM disciplines.

Academic support programs offering tutoring, mentorship, and enrichment activities have improved academic outcomes and retention rates (Jones & Perna, 2013). Financial aid initiatives, such as scholarships and grants specifically targeting underrepresented minorities, have also played a critical role in alleviating the financial burdens that hinder degree completion. Furthermore, efforts to create inclusive and supportive educational environments where Black women feel valued and empowered are essential for fostering their success in STEM. Addressing the multifaceted barriers that Black women face and implementing comprehensive support systems can enhance their representation and achievement in STEM fields, thereby contributing to a more diverse and innovative STEM workforce. Addressing these issues can help close the gap in STEM enrollment intentions and pave the way for greater diversity and innovation in these critical fields.

Moreover, initiatives aimed at fostering inclusive environments and supporting the career advancement of Black women are essential. Such initiatives include creating mentorship programs, offering leadership development opportunities, and implementing policies that actively counteract discrimination and bias (Corneille et al., 2019). Additionally, organizations must commit to transparent hiring and promotion practices and provide training on unconscious bias. By addressing these systemic issues, the STEM community can work towards creating an equitable environment where Black women can thrive and contribute their talents fully.

These results tell a story of persistent systemic challenges and immense opportunity to leverage Black women and girls' unique strengths and potential in STEM through targeted equity-driven reforms. This article provides pertinent data on current trends in AP examination participation, enrollment, degree attainment, and employment to inform the development of profiles for academically advanced Black girls in STEM. More specifically, the present study underscores the resilience and potential of Black women and girls in STEM while illuminating the systemic barriers they face. By aligning educational preparation with workforce demands and addressing inequities in access and support, educators, policymakers, and industry leaders can work together to forge smoother pathways for Black women and girls in STEM. Future research should continue to explore these dynamics, focusing on intersectional and longitudinal analyses that further elucidate the unique experiences of Black women in STEM education and careers. We also hope that higher education researchers and STEM professionals consider these data and our participatory obligations in forging smoother pathways along the STEM pipeline for academically advanced Black girls. Thus, we call for reimagining STEM education and workforce preparation to address structural inequities, promote diversity, and ensure that Black women and girls can fully realize their potential as resilient, creative, and productive STEM contributors.

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References

Arce-Trigatti, P. (2018). The impact of state-mandated advanced placement programs on student outcomes. *Economics of Education Review*, *63*, 180-193. https://doi.org/10.1016/j.econedurev.2018.02.001

Ackerman, P. L., Kanfer, R., & Beier, M. E. (2013). Trait complex, cognitive ability, and domain knowledge predictors of baccalaureate success, STEM persistence, and gender differences. *Journal of Educational Psychology*, *105*(3), 911-927. https://doi.org/10.1037/a0032338

Basile, V., & Lopez, E. (2015). And still I see no changes: Enduring views of students of color in science and mathematics education policy reports. *Science Education*, *99*(3), 519-548. https://doi.org/10.1002/sce.21156

Beale, F. (1970). *Words of fire: An anthology of African-American feminist thought*. W.W. Norton.

Beier, M., & Rittmayer, A. (2008*). Literature overview: Motivational factors in STEM: Interest and self-concept. Assessing women and men in engineering*. Retrieved from https://www.engr.psu.edu/awe/misc/ARPs/ARP_SelfConcept_Overview_122208.pdf

Bianco, M., Harris, B., Garrison-Wade, D., & Leech, N. (2011). Gifted girls: Gender bias in gifted referrals. *Roeper Review*, *33*(3), 170-181. https://doi.org/10.1080/02783193.2011.580500

Bittman, B., Davies, A., Russell, W. & Goussakova, E. (2017). Advanced Placement and the achievement gap in the 21st century: A multiple linear regression of marginalized populations in AP enrollment. *Research in Social Sciences and Technology, 2*(2). https://www.learntechlib.org/p/187535/.

Blackburn, B. R., & Williamson, R. (2013). *Rigorous schools and classrooms: Leading the way*. Routledge.

Blank, M. A., & Antaki, J. F. (2017). Breast lesion elastography region of interest selection and quantitative heterogeneity: a systematic review and meta-analysis. *Ultrasound in medicine & biology*, *43*(2), 387-397. 10.1016/j.ultrasmedbio.2016.09.002

Block, C. J., Cruz, M., Bairley, M., Harel-Marian, T., & Roberson, L. (2019). Inside the prism of an invisible threat: Shining a light on the hidden work of contending with systemic stereotype threat in STEM fields. *Journal of Vocational Behavior*, *113*, 33-50. https://doi.org/10.1016/j.jvb.2018.09.007

Bohrnstedt, G. W., Ogut, B., Yee, D., & Bai, Y. (2023). Ap calculus and science coursetaking: Their relationships with choosing a STEM major and expecting to be in a STEM occupation. *AERA Open*, *9*(1), 1–9. https://doi.org/10.1177/23328584231184426

Bowen, W. G., Kurzweil, M. A., & Tobin, E. M. (2005). *Equity and excellence in American higher education*. University of Virginia Press.

Burnett, M., Cooper, S. M., Butler-Barnes, S. T., & McCoy, W. N. (n.d.). Gendered racial stereotype endorsement: A theoretical review and implications for Black girls' STEM identity. *Journal of African American Women and Girls in Education*, *2*(3), 50–72. https://doi.org/10.21423/jaawge-v2i3a137

Business-Higher Education Forum. (2011). *Creating the workforce of the future: The STEM interest and proficiency challenge*. BHEF Research Brief. Business-Higher Education Forum. https://www.bhef.com/sites/default/files/BHEF_2011_stem_inerest_proficiency.pdf

Card, D., & Giuliano, L. (2016). Universal screening increases the representation of low-income and minority students in gifted education. *Proceedings of the National Academy of Sciences*, *113*(48), 13678-13683. https://doi.org/10.1073/pnas.1605043113

Ceci, S. J., Williams, W. M., & Barnett, S. M. (2009). Women's underrepresentation in science: Sociocultural and biological considerations. *Psychological Bulletin, 135*, 218-261. 10.1037/a0014412

Charleston, L., Adserias, R., Lang, N., & Jackson, J. (2014). Intersectionality and STEM: The role of race and gender in the academic pursuits of African American women in STEM. *Journal of Progressive Policy & Practice*, *2*(3), 273-293. https://caarpweb.org/wp-content/uploads/2014/12/Charleston-Adserias-Lang-Jackson-2014.pdf

Charles, M., & Bradley, K. (2006). A matter of degrees: Female underrepresentation in computer science programs cross-nationally. In J. Cohoon & W. Aspray (Eds), *Women and information technology: research on underrepresentation*. The MIT Press. https://doi.org/10.7551/mitpress/9780262033459.001.0001

Chen, J., Perez-Felkner, L., Nhien, C., Hu, S., Erichsen, K., & Li, Y. (2024). Gender Differences in Motivational and Curricular Pathways Towards Postsecondary Computing Majors. *Research in Higher Education*. https://doi.org/10.1007/s11162-023-09751-w

Clotfelter, C. T., Ehrenberg, R. G., Getz, M., & Siegfried, J. J. (2008). Economic challenges in higher education. University of Chicago Press.

College Board. (2012). AP Potential. Retrieved from https://appotential.collegeboard.org/app/welcome.do

College Board (2020, September). Supporting students from day one to exam day. https://apcentral.collegeboard.org/

Collins, K. H., Joseph, N. M., & Ford, D. Y. (2020). Missing in Action: Gifted Black Girls in Science, Technology, Engineering, and Mathematics. *Gifted Child Today*, *43*(1), 55-63. https://doi.org/10.1177/1076217519880593

Corneille, M., Lee, A., Allen, S., Cannady, J., & Guess, A. (2019). Barriers to the advancement of women of color faculty in STEM: The need for promoting equity using an intersectional framework. *Equality, Diversity and Inclusion: An International Journal*, *38*(3), 328-348.

Cumming, G., & Finch, S. (2001). A primer on the understanding, use, and calculation of confidence intervals that are based on central and non-central distributions. *Educational and Psychological Measurement, 61*, 532-574.

Davis, J. L. (2010). *Bright, talented, and Black: A guide for families of African American gifted learners*. Great Potential Press.

Davis, J. L., & Moore, J. L. (2016). *Gifted children of color around the world: Diverse needs, exemplary practices and directions for the future*. Emerald Publishing.

Dickens, D. D., Ellis, V., & Hall, N. M. (2021). Changing the face of STEM: review of literature on the role of mentors in the success of undergraduate Black women in STEM education. *Journal of Research Initiatives*, *5*(3), 1–11.

Diekman, A. B., Clark, E. K., Johnston, A. M., Brown, E. R., & Steinberg, M. (2011). Malleability in communal goals and beliefs influences attraction to STEM careers: Evidence for a goal congruity perspective. *Journal of Personality and Social Psychology, 101*, 902–918. https://doi.org10.1037/a0025199

Eagan, M. K., Stolzenberg, E. B., Ramirez, J. J., Aragon, M. C., Suchard, M. R., & Rios-Aguilar, C. (2016). The American freshman: Fifty-Year trends, 1966-2015. Los Angeles, CA:

Ecker-Lyster, M., & Niileksela, C. (2017). Enhancing gifted education for underrepresented students: Promising recruitment and programming strategies. *Journal for the Education of the Gifted, 40*(1), 79-95. https://doi.org/10.1177/0162353216686216

Espinosa, L. (2011). Pipelines and pathways: Women of color in undergraduate STEM majors and the college experiences that contribute to persistence. *Harvard Educational Review, 81*(2), 209-241. https://doi.org/10.17763/haer.81.2.92315ww157656k3u

Farinde, A. A., & Lewis, C. W. (2012). The underrepresentation of African American female students in STEM fields: Implications for classroom teachers. *US-China Education Review, B*(4), 421-430. https://files.eric.ed.gov/fulltext/ED533550.pdf

Feller, R. (2012, June 19). 10 startling stats about minorities in STEM. *STEM Career.* http://stemcareer.com/2012/06/10-startling-stats-about-minorities-in-stem/

Fletcher, T. L., Jefferson, J. P., Boyd, B. N., & Cross, K. J. (2023). Missed opportunity for diversity in engineering: Black women and undergraduate engineering degree attainment. *Journal of College Student Retention*, *25*(2), 350–377. https://doi.org/10.1177/1521025120986918

Ford, D. Y. (2010a). Underrepresentation of culturally different students in gifted education: Reflections about current problems and recommendations for the future. *Gifted Child Today*, *33*(3), 31-35. https://doi.org/10.1177/107621751003300308

Ford, D. Y. (2010b). Reversing underachievement among gifted Black students: Theory, research and practice (2nd ed.). Prufrock Press.

Ford, D. Y. (2014). Segregation and the underrepresentation of Blacks and Hispanics in gifted education: Social inequality and deficit paradigms. *Roeper Review*, *36*(3), 143-154. https://doi.org/10.1080/02783193.2014.919563

González-Pérez, S., Mateos de Cabo, R., & Sáinz, M. (2020). Girls in STEM: Is it a female role-model thing? *Frontiers in Psychology*, *11*. https://doi.org/10.3389/fpsyg.2020.02204

Hagedorn, L. S., & DuBray, D. (2010). Math and science success and nonsuccess: Journeys within the community college. *Journal of Women and Minorities in Science and Engineering, 16*(1), 31–50. https://10.1615/JWomenMinorScienEng.v16.i1.30

Hallett, R. E., & Venegas, K. M. (2011). Is increased access enough? Advanced placement courses, quality, and success in low-income urban schools. *Journal for the Education of the Gifted*, *34*(3), 468-487. https://doi.org/10.1177/016235321103400305

Hanson, S. L. (2004). African American women in science: Experiences from high school through the post- secondary years and beyond. *National Women's Study Association Journal, 16*(1), 96–115. Retrieved from https://muse.jhu.edu/article/168389

Heafner, T. L., & Fitchett, P. G. (2015). An opportunity to learn U.S. history: What NAEP data suggest regarding the opportunity gap. *The High School Journal*, *98*(3), 226-249. 10.1353/hsj.2015.0006

Henfield, M. S., Moore III, J. L., & Wood, C. (2008). Inside and outside gifted education programming: Hidden challenges for African American students. *Exceptional Children*, *74*(4), 433-450. https://doi.org/10.1177/001440290807400402

Hertberg-Davis, H., & Callahan, C. M. (2008). A narrow escape: Gifted students' perceptions of Advanced Placement and International Baccalaureate programs. *Gifted Child Quarterly*, *52*(3), 199–216. https://doi.org/10.1177/0016986208319705

Hill, C., Corbett, C., & Rose. A. (2010). *Why so few? Women in science, technology, engineering, and mathematics.* American Association of University Women.

Hirschl, N., & Smith, C. M. (2023). Advanced placement gatekeeping and racialized tracking. *Sociology of Education*, *96*(3), 190–210. https://doi.org/10.1177/00380407231161334

Ireland, D. T., Freeman, K. E., Winston-Proctor, C. E., DeLaine, K. D., McDonald Lowe, S., & Woodson, K. M. (2018). (Un)hidden figures: A synthesis of research examining the intersectional experiences of Black women and girls in STEM education. *Review of Research in Education*, *42*(1), 226–254. https://doi.org/10.3102/0091732X18759072

James, M. C., Butterfield, V., Jones, K. L., & Mokuria, V. G. (2017). Opportunity for all: An analysis of equality and equity in advanced placement programming in a U.S. high school. *International Journal of Innovation and Research in Educational Sciences, 4*(1), 15-21. https://www.ijires.org/administrator/components/com_jresearch/files/publications/IJIRES_748_FINAL.pdf

Jaumot-Pascual, N., Ong, M., Silva, C., & Martínez-Gudapakkam, A. (2021). Women of color leveraging Community Cultural Wealth to persist in computing and tech graduate education: A qualitative meta-synthesis. *Education Sciences*, *11*(12), Article 12. https://doi.org/10.3390/educsci11120797

Jewett, E., & Chen, R. (2022). Examining the relationship between AP STEM course-taking and college major selection: Gender and racial differences. *Journal of Engineering Education*, *111*(3), 512–530. https://doi.org/10.1002/jee.20464

Johnson, D. R. (2011). Women of color in science, technology, engineering, and mathematics (STEM). *New Directions for Institutional Research*, *2011*(152), 75-85. https://doi.org/10.1002/ir.410

Jones, A. P., & Perna, L. (2013). The state of college access and completion: Improving college success for students from underrepresented groups. *NY: Routledge.*

Kettler, T., Russell, J., & Puryear, J. S. (2015). Inequitable access to gifted education: Variance in funding and staffing based on locale and contextual school variables. *Journal for the Education of the Gifted*, *38*(2), 99-117. https://doi.org/10.1177/0162353215578277

King, D. K. (2016). Multiple jeopardy, multiple consciousness: The context of a Black feminist ideology. In *race, gender and class* (pp. 36-57). Routledge.

King, N. S. (2021). Toward an equity agenda for Black girls and women in STEM learning spaces and careers: Noticing, validating, and humanizing. *Journal of African American Women and Girls in Education*, 1-9 Pages. https://doi.org/10.21423/jaawge-v1i2a93

Klopfenstein, K., & Lively, K. (2016). Do grade weights promote more advanced course-taking?. *Education Finance and Policy*, *11*(3), 310-324. https://doi.org/10.1162/EDFP_a_00182

Knezek, G. (2015). Gender Differences in Conceptualizations of STEM Career Interest: Complementary Perspectives from Data Mining, Multivariate Data Analysis and Multidimensional Scaling. *Journal of STEM Education, 16*(4). https://www.learntechlib.org/p/171343/

Krakehl, R., & Kelly, A. (2021). Intersectional analysis of Advanced Placement Physics participation and performance by gender and ethnicity. *Physical Review Physics Education Research*, *17*(2). https://doi.org/10.1103/PhysRevPhysEducRes.17.020105

Leaper, C., & Brown, C. S. (2008). Perceived experiences with sexism among adolescent girls. *Child Development, 79*, 685-704. https://doi.org/10.1111/j.1467-8624.2008.01151.x

Lofton, R. (2021). Plessy's Tracks: African American students confronting academic placement in a racially diverse school and African American community. *Race Ethnicity and Education*, *0*(0), 1–20. https://doi.org/10.1080/13613324.2021.1924141

Maltese, A. V., & Tai, R. H. (2011). Pipeline persistence: Examining the association of educational experiences with earned degrees in STEM among US students. *Science education*, *95*(5), 877-907. https://doi.org/10.1002/sce.20441

Mayes, R. D., & Hines, E. M. (2014). College and career readiness for gifted African American girls: A call to school counselors. *Interdisciplinary Journal of Teaching and Learning*, *4*(1), 31-42. https://files.eric.ed.gov/fulltext/EJ1063071.pdf

McGee, E. O. (2021). *Black, brown, bruised: How racialized STEM education stifles innovation.* Harvard Education Press.

McGee, E., & Bentley, L. (2017). The equity ethic: Black and Latinx college students reengineering their STEM careers toward justice. *American Journal of Education*, *124*(1), 1–36. https://doi.org/10.1086/693954

Mickelson, R. A., & Greene, A. D. (2006). Connecting pieces of the puzzle: Gender differences in Black middle school students' achievement. *Journal of Negro Education, 75*, 34 – 48.

Miller, C.C. (2013, April) Opening a gateway for girls to enter the computer field. *The New York Times*. http://dealbook.nytimes.com/2013/04/02/opening-a- gateway-for-girls-to-enter-the-computer-field/?src=twrhp

National Center for Science and Engineering Statistics (NCSES). 2023. *Diversity and STEM: Women, Minorities, and Persons with Disabilities 2023*. Special Report NSF 23-315. Alexandria, VA: National Science Foundation. Available at https://ncses.nsf.gov/wmpd.

National Association for Gifted Children. (2014). *2012–2013 state of the nation in gifted education: Work yet to be done.* https://www.nagc.org/sites/default/files/Advocacy/State%20of%20the%20Nation.pdf

National Research Council. (2013). *Education for life and work: Developing transferable knowledge and skills in the 21st century*. National Academies Press.

National Science Foundation, National Center for Science and Engineering Statistics.(2013). *Women, Minorities, and Persons with Disabilities in Science and Engineering: 2013*. Special Report NSF 13-304. http://www.nsf.gov/statistics/wmpd

Nix, S., & Perez-Felkner, L. (2019). Difficulty orientations, gender, and race/ethnicity: An intersectional analysis of pathways to STEM degrees. *Social Sciences*, *8*(2), Article 2. https://doi.org/10.3390/socsci8020043

O'Connor, C., Mueller, J., Lewis, R. L., Rivas-Drake, D., & Rosenberg, S. (2011). "Being" Black and strategizing for excellence in a racially stratified academic hierarchy. *American Educational Research Journal*, *48*(6), 1232–1257. https://doi.org/10.3102/0002831211410303

Office of Civil Rights. (2020, August). *Educational equity report.* https://ocrdata.ed.gov/DataAnalysisTools/DataSetBuilder?Report=7

Ong, M., Jaumot-Pascual, N., & Ko, L. T. (2020). Research literature on women of color in undergraduate engineering education: A systematic thematic synthesis. *Journal of Engineering Education*, *109*(3), 581-615. https://doi.org/10.1002/jee.20345

Ong, M., Wright, C., Espinosa, L., & Orfield, G. (2011). Inside the double bind: A synthesis of empirical research on undergraduate and graduate women of color in science, technology, engineering, and mathematics. *Harvard Educational Review*, *81*(2), 172–209. https://doi.org/10.17763/haer.81.2.t022245n7x4752v2

Park, K., Caine, V., & Wimmer, R. (2014). The experiences of Advanced Placement and International Baccalaureate diploma program participants: A systematic review of qualitative research. *Journal of Advanced Academics*, *25*(2), 129–153. https://doi.org/10.1177/1932202X14532258

Pepitone, J. (2013, March 18). Black, female, and a Silicon Valley's Trade secret. *CNN*. https://money.cnn.com/2013/03/17/technology/diversity-silicon-valley/

Perez-Felkner, L., McDonald, S. K., Schneider, B., & Grogan, E. (2012). Female and male adolescents' subjective orientations to mathematics and the influence of those orientations on postsecondary majors. *Developmental Psychology, 48*, 1658-1673. https://doi.org/10.1037/a0027020

Perez-Felkner, L., Nix, S., & Thomas, K. (2017). Gendered pathways: How mathematics ability beliefs shape secondary and postsecondary course and degree field choices. *Frontiers in Psychology*, *8*. https://doi.org/10.3389/fpsyg.2017.00386

Riegle-Crumb, C., & King, B. (2010). Questioning a white male advantage in STEM:

Examining disparities in college major by gender and race/ethnicity. *Educational Researcher*, *39*(9), 656-664. https://doi.org/10.3102/0013189X1039165

Riegle-Crumb, C., Moore, C., & Ramos-Wada, A. (2011). Who wants to have a career in science or math? Exploring adolescents' future aspirations by gender and race/ethnicity. *Science Education*, *95*(3), 458-476. https://doi.org/10.1002/sce.20431

Rodriguez, A., & McGuire, K. M. (2019). More classes, more access? Understanding the effects of course offerings on black-white gaps in advanced placement course-taking. *The Review of Higher Education*, *42*(2), 641–679. https://doi.org/10.1353/rhe.2019.0010

Sadler, P. M., Sonnert, G., Hazari, Z., & Tai, R. (2012). Stability and volatility of STEM career interest in high school: A gender study. *Science education*, *96*(3), 411-427. https://doi.org/10.1002/sce.21007

Saunders, J., Davis, L., Williams, T., & Williams, J. H. (2004). Gender differences in self-perceptions and academic outcomes: A study of African American high school students. *Journal of Youth and Adolescence*, *33*(1), 81-90. https://doi.org/10.1023/A:1027390531768

Sendze, M. S. (2023). I can't quit: Experiences of Black women in STEM professions. *Journal of Career Assessment*, *31*(2), 377–396. https://doi.org/10.1177/10690727221118696

Shapiro, T. M. (2004). *The hidden cost of being African American: How wealth perpetuates inequality*. Oxford University Press.

Speroni, C. (2011). Determinants of students' success: The role of Advanced Placement and dual enrollment programs. An NCPR working paper. In *National Center for Postsecondary Research*. National Center for Postsecondary Research. https://eric.ed.gov/?id=ED527528

Snyder, T. D., & Dillow, S. A. (2009). *Digest of education statistics, 2008*. Government Printing Office. http://hdl.voced.edu.au/10707/380346.

Stout, J. G., Dasgupta, N., Hunsinger, M., & McManus, M. A. (2011). STEMing the tide: Using ingroup experts to inoculate women's self-concept in science, technology, engineering, and mathematics (STEM). *Journal of Personality and Social Psychology, 100*, 255–270. https://doi.org/10.1037/a0021385

Taylor, T. Y. (2017). *Perceptions of peer group interactions on self-efficacy and academic identity of African-American students in advanced placement classes* (Doctoral dissertation, University of Louisville, Louisville, KY). Retrieved from https://ir.library.louisville.edu/etd/2743/

Theokas, C. & Bromberg, M. (2014). *Falling out of the lead: Following high achievers through high school and beyond*. Education Trust.

Theokas, C., & Saaris, R. (2013). *Shattering expectations: Finding America's missing AP and IB students*. Education Trust. https://files.eric.ed.gov/fulltext/ED578802.pdf

Tholen, A., Edosomwan, K., Hong, D., Fulmer, G. W., & Young, J. (2022). Increasing access to advanced mathematics through self-selection: A multinomial logistic regression analysis. *The High School Journal*, *105*(2), 145–169. https://doi.org/10.1353/hsj.2022.0003

Thomas, J. O., Joseph, N., Williams, A., Crum, C., & Burge, J. (2018). Speaking truth to power: Exploring the intersectional experiences of black women in computing. *2018 Research on Equity and Sustained Participation in Engineering, Computing, and Technology (RESPECT)*, 1–8. https://doi.org/10.1109/RESPECT.2018.8491718

Tugend, A. (2017, September 7). Who benefits from the expansion of AP classes? *The New York Times Magazine*. https://www.nytimes.com/2017/09/07/magazine/who-benefits-from-the-expansion-of-ap-classes.html

U.S. Department of Education Office of Civil Rights. (2018). *Civil Rights Data Collection (CRDC) for the 2015-16 School Year*. https://www2.ed.gov/about/offices/list/ocr/docs/crdc-2015-16.html?utm_content=&utm_medium=email&utm_name=&utm_source=govdelivery&utm_term

U.S. Department of Education, Office for Civil Rights. (2015). *Civil Rights Data Collection (CRDC) for the 2013-14 School Year*. https://www2.ed.gov/about/offices/list/ocr/docs/crdc-2013-14.html

Varner, F., & Mandara, J. (2013). Discrimination concerns and expectations as explanations for gendered socialization in African American families. *Child development*, *84*(3), 875-890. https://doi.org/10.1111/cdev.12021

Wang, M. T., & Degol, J. (2013). Motivational pathways to STEM career choices: Using expectancy–value perspective to understand individual and gender differences in STEM fields. *Developmental Review*, *33*(4), 304-340. https://doi.org/10.1016/j.dr.2013.08.001

Warne, R. T., Sonnert, G., & Sadler, P. M. (2019). The Relationship Between Advanced Placement Mathematics Courses and Students' STEM Career Interest. *Educational Researcher*, *48*(2), 101-111. https://doi.org/10.3102/0013189X19825811

Woolley, M. E., Strutchens, M., Gilbert, M. C., & Martin, W. G. (2010). Mathematics success of Black middle school students: Direct and indirect effects of teacher expectations and reform practices. *Negro Educational Review*, *61*(1-4), 41-59.

Xu, D., Solanki, S., & Fink, J. (2021). College acceleration for all? Mapping racial gaps in advanced placement and dual enrollment participation. *American Educational Research Journal*, *58*(5), 954–992. https://doi.org/10.3102/0002831221991138

Yamaguchi, R., & Burge, J. D. (2019). Intersectionality in the narratives of black women in computing through the education and workforce pipeline. *Journal for Multicultural Education*, *13*(3), 215–235. https://doi.org/10.1108/JME-07-2018-0042

Young J. L. (2016a). From special ed to higher ed: A Black girl's journey in discovering her giftedness. In Ford D., Davis J., Trotman Scott M., Sealey-Ruiz Y. (Eds.), *Gumbo for the soul: Liberating stories to inspire females of color*. Charlotte, NC: Information Age.

Young J. L. (2016b). Access, achievement, and academic resilience: The relationship between AVID and Black student participation in advanced placement courses. *Journal of Multicultural Affairs*, 1(2), 1–26. https://scholarworks.sfasu.edu/jma/vol1/iss2/4

Young, J. (2020). To Heal Our World, We Must First Heal Our Girls: Examining Black Girl Achievement. *Multicultural Learning and Teaching*, *15*(2), 1-11. https://doi.org/10.1515/mlt-2016-0022

Young, J. L., Ero-Tolliver, I., Young, J. R., & Ford, D. Y. (2017). Maximizing opportunities to enroll in advanced high school science courses: Examining the scientific dispositions of Black girls. *Journal of Urban Learning, Teaching, and Research*, *13*, 174-183. https://files.eric.ed.gov/fulltext/EJ1149860.pdf

Young, J. L., Feille, K. K., & Young, J. R. (2017). Black girls as learners and doers of science: A single-group summary of elementary science Achievement. *Electronic Journal of Science Education*, *21*(2), 1-20. https://files.eric.ed.gov/fulltext/EJ1187988.pdf

Young, J. L., & Larke, P. J. (2017). One book and one girl at a time: Analyzing and explaining Black girl's reading achievement in elementary school. *Literacy and Social Responsibility*, *9*(1), 3-10.

Young, J. L., Young, J. R., & Capraro, R. M. (2018). Gazing past the gaps: A growth-based assessment of the mathematics achievement of Black girls. *The Urban Review*, *50*, 156-176. https://doi.org/10.1007/s11256-017-0434-9

Young, J. L., Young, J. R., & Capraro, R. M. (2020). Advancing Black girls in STEM: Implications from advanced placement participation and achievement. *International Journal of Gender, Science and Technology*, *12*(2), 202-222. https://genderandset.open.ac.uk/index.php/genderandset/article/view/566

Young, J. L., Young, J. R., & Capraro, M. M. (2017). Black girls' achievement in middle grades mathematics. *The Clearing House*, *90*(3), 70-76. https://doi.org/10.1080/00098655.2016.1270657

Young, J. L., Young, J. R., & Ford, D. Y. (2017). Standing in the gaps: Examining the effects of early gifted education on Black girl achievement in STEM. *Journal of Advanced Academics*, *28*(4), 290-312. https://doi.org/10.1177/1932202X17730549

Young, J. L., Young, J. R., & Ford, D. Y. (2019). Culturally relevant STEM out-of-school time: A rationale to support gifted girls of color. *Roeper Review*, *41*(1), 8-19. https://doi.org/10.1080/02783193.2018.1553215

Zientek, L. R., Thompson, B., & Yetkiner, Z. E. (2010). Characterizing the mathematics anxiety literature using confidence intervals as a literature review mechanism. The *Journal of Educational Research, 103*, 424-438.

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Prospective Teachers' Noticing of Students' Algebraic Thinking: The Case of Pattern Generalization

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ABSTRACT

This study aimed to investigate prospective middle school mathematics teachers' noticing of students' algebraic thinking based on students' correct and incorrect solutions within the context of pattern generalization. Designed as a qualitative case study, three noticing prompts were asked of thirty-two prospective middle school mathematics teachers. Along with it, a semi-structured interview was conducted with eight prospective teachers out of thirty-two prospective teachers. The findings of this study demonstrated that while most prospective teachers could attend to the students' correct and incorrect solutions, they had difficulty interpreting the students' algebraic thinking. The prospective teachers even provided less evidence to interpret the algebraic thinking of the student with the incorrect solution than with the correct solution. Finally, although a vast majority of the prospective teachers could support the algebraic thinking of the student having an incorrect solution, they could not extend the algebraic thinking of the student having a correct solution.

Keywords: correct and incorrect solution; pattern generalization; professional noticing of children's mathematical thinking; students' algebraic thinking; teacher noticing

Introduction

Rather than being a haphazard act, noticing is an intentional act performed consistently within various contexts (Mason, 2011). For more than two decades, many researchers have paid greater attention to how people notice their environment and have approached noticing from a professional point of view (Goodwin, 1994; Stevens & Hall, 1998). For instance, Goodwin (1994) used the term "professional vision" to explain how members of a profession revealed and developed a perceptual framework that allowed them to recognize complicated situations in certain ways. If it is adapted to the context of teaching, professional vision refers to the ability to interconnect theoretical knowledge and practice by noticing the noteworthy events in complex classroom environments (Blömeke et al., 2015; Goodwin, 1994). Professional vision helps teachers notice the classroom environment and, specifically, students' thinking, and it is considered an indispensable skill and a prerequisite for effective teaching (Grossman et al., 2009).

Teacher noticing is an active process rather than a static category of knowledge. It includes the skills of analyzing remarkable events in a classroom setting in which everything simultaneously occurs and the ability to tackle these complex events (Jacobs et al., 2010; Star & Strickland, 2008; van Es & Sherin, 2002, 2021). Teacher noticing also requires teachers to be knowledgeable about the ways students' solutions are not meaningful, as well as to be alert to the correctness of their answers (Holt et al., 2013; Jacobs et al., 2010; van Es, 2011). Thus, teacher noticing, as a skill, is an important dynamic competency required for all teachers, and mathematical teaching could be enriched further by paying more attention to these skills (Franke et al., 2001; Goodwin, 1994; Kaiser et al., 2015).

The significance of teacher noticing skills is not a matter of dispute among scholars, but previous research has explored teacher noticing by confining it to either teachers' correct mathematical thinking (Tyminski et al., 2021) or incorrect mathematical thinking (Copur-Genckturk & Rodrigues, 2021; Girit-Yıldız et al., 2022). Investigating teachers' noticing by focusing on students' both correct and incorrect solutions gives more detailed implications about teachers' expertise. More specifically, as mentioned by Chick et al. (2006), students' correct solutions provided a more significant opportunity to attend to the steps of students' solutions and interpret students' understanding based on the important issues of the related subject. However, previous studies (e.g., Crespo, 2002) indicated that incorrect students' solutions required identifying at what stage students made errors and defining the reasons for making these errors. In order to notice students' incorrect solutions, teachers need to attend to students' errors/difficulties/misconceptions, interpret students' thoughts on the causes of their errors, and decide how to support students' understanding. In other words, teachers need to uncover the reasons for students' incorrect solutions, which enables teachers to make better instructional decisions. In addition, although noticing students' incorrect mathematical understanding is crucial for effective mathematics teaching, not as many studies have been conducted with the intention of noticing students' incorrect reasoning as those focused on identifying students' accurate reasoning (Shaughnessy et al., 2021). Thus, based on the advantages of correct and incorrect responses, the present study focused on prospective teachers' noticing skills of students' correct and incorrect reasoning.

Empirical research has consistently demonstrated that teachers' professional noticing is inherently domain-specific. As a result, it is essential to examine teachers' noticing skills across distinct mathematical domains in order to identify areas requiring development from a subject-specific perspective (Jacobs & Empson, 2016; Ivars et al., 2020; Nickerson et al., 2017). Informed by these findings, the present study investigates the domain-specific nature of professional noticing, with a particular focus on the mathematical context of algebra, for the following reasons. Algebra is one of the key mathematical domains that teachers must attend to and interpret effectively, as it is widely regarded as a gatekeeper in mathematics education due to its foundational role in supporting the development of more advanced mathematical concepts (Blanton & Kaput, 2005; Knuth et al., 2005; Rakes et al., 2010). Additionally, the algebra domain offers a particularly productive context to investigate teachers' noticing based on students' correct and incorrect answers because algebra, by its nature, provides both correct and incorrect examples, which in turn leads to better learning performances for students (Curry, 2004; Jurdak & El Mouhayar, 2014; Lannin et al., 2006). Therefore, the current study aimed to explore how prospective middle school mathematics teachers notice students' algebraic thinking based on their correct and incorrect solutions.

Theoretical Framework

A great deal of research on teacher noticing was predominantly conducted by drawing on two main theoretical frameworks: "Learning to Notice" and "Professional Noticing of Children's

Mathematical Thinking." Within the Learning to Notice framework, van Es (2011) focused on two dimensions with four levels of teacher noticing: "what teachers notice" and "how teachers notice." The former is related to teachers' observation of students' understanding as a group, classroom environment, and teachers' pedagogy, whereas the latter is related to how teachers analyze and evaluate what they observe (van Es, 2011). van Es described the levels of both dimensions from general to specific, i.e., baseline, mixed, focused, and extended levels. Later, van Es and Sherin (2021) expanded their framework by taking into consideration that noticing was an active process and took place in a context. The revised framework consists of students' understanding and interpretation of solution strategies as well as the shaping of the new dimension.

On the other hand, Jacobs et al. (2010) focused on the fourth level of van Es's framework, which was defined as understanding particular students' thinking and teachers' in-the-moment decisions while responding to students based on their mathematical thinking. In that respect, they put forth "Professional Noticing of Children's Mathematical Thinking" by centering on students' thinking. Since the researchers of the present study aimed to focus on prospective teachers' noticing from the point of a particular student's thinking through students' written solutions rather than the whole classroom setting, the study was grounded on professional noticing of students' mathematical thinking. Written works/solutions serve as an authentic activity for interpreting students' thinking and responding to students based on their thinking for mathematics teaching (Grosman et al., 2009; Jacobs & Philipp, 2004). Thus, given that prospective teachers are teachers in the future, examining their noticing skills through students' written solutions is essential. By building the current study on this framework, the researchers aimed to fill the gap in the relevant literature as to the extent to which prospective teachers noticed students' both correct and incorrect written solutions in the context of a particular mathematical domain, that was, algebra. Similar to Jacobs et al.'s (2010) study, how prospective teachers capture the mathematically noteworthy details in students' written solutions, how they presented evidence regarding their thoughts when evaluating students' written solutions, and how they used this interpretation when responding to students were emphasized.

Professional Noticing of Children's Mathematical Thinking

Professional noticing of children's mathematical thinking, which the current study was preoccupied with, focuses on how and to what extent teachers notice children's mathematical thinking rather than what teachers notice (Jacobs et al., 2010). Professional noticing of children's mathematical thinking consists of three important components: "(1) attending to children's strategies, (2) interpreting children's understanding, and (3) deciding how to respond based on children's understandings" (Jacobs et al., 2010, p. 169). Attending to children's strategies is related to teachers' identification of remarkable mathematical essence in children's strategies (Jacobs et al., 2010). Jacobs et al. (2010) classified teachers' attending skills as proof of whether they attended to children's strategies.

On the other hand, interpreting children's understanding is associated with teachers' analysis and interpretation of children's mathematical understanding based on their strategies (Jacobs et al., 2010). Finally, deciding how to respond, based on children's understanding, is tied to teachers' decisions to respond to children and teachers' reasoning for their decisions (Jacobs et al., 2010). Within this framework, Jacobs et al. (2010) categorized teachers' skills of interpreting and deciding how to respond into three areas: robust evidence, limited evidence, and lack of evidence. Therefore, it would not be wrong to suggest that Jacobs and his colleagues were interested in teachers' noticing each child's mathematical understanding and teachers' in-the-moment decisions to respond to the child rather than focusing on the whole group's mathematical thinking, teacher's pedagogy, or classroom environment (Jacobs et al., 2010; LaRochelle, 2018).

Algebraic Thinking and Pattern Generalization

Algebra is considered a foundation for conceptualizing many advanced mathematical concepts, and it comprises abilities like how variables relate to one another, generalizing that relationship, and using that generalization to formulate a rule using an algebraic expression (Kaput, 1999). The National Council of Teachers of Mathematics (NCTM, 2000) established the objectives that students must meet in order to master algebra under this definition. These objectives included comprehending patterns, relationships, and functions as well as applying algebraic symbols to analyze mathematical situations and structures. These objectives also involved studying change in various contexts and using mathematical models to describe and interpret quantitative relationships. In order to achieve these goals, students need to have and develop their algebraic thinking, which is defined as interpreting symbols and algebraic operations as arithmetic (Kieran & Chalouh, 1993) and being able to make sense of unknown quantities as known quantities with different representations (Swafford & Langrall, 2000).

One of the practical methods of mathematical reasoning that aids students in the transition from arithmetic to algebra is designated as algebraic thinking (Radford, 2008). In other words, students should first be introduced to algebra through an operational perspective before advancing to a structural understanding (Carraher & Schliemann, 2007; Sfard, 1995). This transition typically occurs via a pattern generalization process, which consists of three distinct phases (Radford, 2008; Stacey, 1989):

1. Near Term Generalization: Identifying a recurring process using a step-by-step approach, including drawing and counting.
2. Far-Term Generalization: Extending the generalization to address problems that exceed the limitations of the step-by-step method, such as determining the number of elements in the 80th figure of a pattern.
3. Rule Formulation: Developing a formal rule or formula to describe and define the sequence.

Through the process of pattern generalization, students can express relations that are expressed arithmetically with letters, which results in algebraic thinking. Pattern generalization, expressing the relationship between variables algebraically, is a challenging process for students due to the necessity for a step-by-step solution (Jurdak & Mouhayar, 2014). However, if teachers can comprehend how students construct symbols in their minds and generalize the pattern algebraically, they can create a more effective learning environment for algebra. Therefore, teachers' professional noticing of students' algebraic thinking is crucial for teachers to enhance students' algebraic thinking and teach algebra more effectively (Radford, 2008).

The Rationale of the Study

Relevant literature demonstrates that a great deal of research has been conducted to investigate how teachers notice students' mathematical thinking within specific mathematical contexts (Kılıç & Doğan, 2021; Lee, 2019; Sánchez-Matamoros et al., 2019; Taylan, 2017). In prior studies conducted within the context of algebra, researchers explored teachers' professional noticing of children's algebraic thinking through either video club meetings or student work (LaRochelle et al., 2019; Walkoe, 2013; Zapatera & Callejo, 2013). Even though the current study acknowledged such studies and aimed to attain a similar objective, exploring prospective teachers' noticing skills by utilizing students' both correct and incorrect solutions made the study significant and contributed to relevant literature.

Correct and incorrect solutions have diverse attributes, so teachers must highlight different aspects of students' correct and incorrect solutions to notice their mathematical thinking. First, to notice students' correct solutions, prospective teachers have to pay attention to different ways to solve a problem and analyze how students think. On the other hand, to notice students' incorrect solutions, prospective teachers need to attend to students' conceptual and procedural mistakes/misconceptions and understand the reasons why these students have such difficulties. Second, due to the nature of the pattern generalization, students must solve the problem step-by-step in order to formulate a general rule (Jurdak & El Mouhayar, 2014; Lannin et al., 2006). Thus, it can clearly be observed how students arrive at the correct solution through a step-by-step process.

However, it is challenging to determine at which stages of pattern generalization students make mistakes and/or have misconceptions that lead them to incorrect solutions. Moreover, students' correct and incorrect solutions have critical roles in examining whether teachers can extend/support the mathematical thinking of students with correct and incorrect solutions (Jacobs et al., 2010). Finally, researchers who have investigated students' thinking through video club meetings or student work focus on either only students' correct mathematical thinking (Tyminski et al., 2021) or incorrect mathematical thinking (Copur-Genckturk & Rodrigues, 2021; Girit-Yıldız et al., 2022). Therefore, it is crucial to examine prospective teachers' noticing of students' algebraic thinking using both correct and incorrect solutions to portray the whole picture of teachers' expertise in attending, interpreting, and deciding how to respond. Furthermore, Jacobs and Ambrose (2008) and Milewski and Strickland (2016) examined teachers' moves to improve students' thinking using two different categorizations: correct and incorrect answers. This categorization also proves that investigating teachers' noticing of students' both correct and incorrect solutions is significant.

Moreover, the categorization of Jacobs et al.'s framework did not cover all the data gathered from the prospective teachers. For this reason, it was necessary to extend Jacobs et al.'s framework to enable a detailed analysis of all skills. The first component of professional teacher noticing -attending to students' solutions- includes two categories: evidence of attending and lack of evidence of attending (Jacobs et al., 2010). However, in this study, some prospective teachers' responses could not be categorized under the evidence of attending or lack of evidence. Thus, to categorize all prospective teachers' responses, two more categories, namely emerging evidence and limited evidence of attending to students' solutions, were added based on the common characteristics of responses. The second component of professional teacher noticing -interpreting students' algebraic thinking- is analyzed under three categories: robust evidence, limited evidence, and lack of evidence (Jacobs et al., 2010). However, because some participants' responses did not match the characteristics of robust evidence or limited evidence, there was a need to add one more category, emerging evidence, between robust and limited evidence.

Furthermore, the third component of professional teacher noticing -deciding how to respond- includes three categories: robust evidence, limited evidence, and lack of evidence (Jacobs et al., 2010). However, this study revealed that prospective teachers either asked questions to develop and extend students' existing understanding or they posed structurally similar questions that were repetitive in nature and failed to connect with or extend the student's current thinking. Therefore, the participants' skill of deciding how to respond was coded under three categories: extending/supporting students' algebraic thinking, *reinforcing procedural understanding*, and providing a general response. Finally, this categorization prepared for student's correct and incorrect solutions separately, which made the present study necessary. Detailed information about the categories used in this study was given in Table 1-2-3 in the findings section.

Lastly, using data from a natural classroom environment instead of taking student solutions from the literature could contribute to the scholarship about students' strategies in pattern generalization tasks. In order to put students' solutions to the questionnaire for teachers, a problem about pattern generalization was asked of 115 6th-grade students. Among their solutions, two solutions (one correct and one incorrect), including noteworthy mathematical details, were used to collect data from the prospective teachers. Therefore, in this research study, how prospective teachers attended to real student solutions obtained from math classes, interpreted students' algebraic thinking, and the nature of their decisions to respond to students were examined. Thus, the following research questions guided the research study:

1. How do prospective middle school mathematics teachers attend to students' correct and incorrect solutions of pattern generalization?
2. How do prospective middle school mathematics teachers interpret students' algebraic thinking based on students' correct and incorrect solutions within the context of pattern generalization?
3. What is the nature of the decisions that prospective middle school mathematics teachers make to respond based on students' correct and incorrect algebraic thinking within the context of pattern generalization?

Methods

Research Design

This study aimed to offer a deeper systematic examination of prospective middle school mathematics teachers' noticing of students' correct and incorrect solutions, so a qualitative case study was decided to be an appropriate research design to undertake such a study (Creswell, 2007; Merriam, 1998). A case study focuses on the process, context, and discovery instead of outcomes and specific variables. In addition, it enables an in-depth understanding of an issue through the opportunity of detailed data collection and analysis (Creswell, 2007; Merriam, 1998). In this sense, the case of this study was a group of prospective middle school mathematics teachers all studying their last year at the university at the same time, and the units of the analysis were the teachers' skills of attending to students' solutions, interpreting students' mathematical understanding, and deciding how to respond. Since there was a single case and three units of analysis (Yin, 2009) in the present study, the model of the single-case embedded design was preferred.

Questionnaires and semi-structured interviews are essential data collection tools to construct case studies appropriately (Merriam, 1998). "Open-ended questions will result in more detailed and useful data than questions that can be answered with a yes or no" (Moore et al., 2012, p.256). For this reason, open-ended questions in questionnaires and interviews facilitate in-depth understanding and detailed insights into participants' thoughts, experiences, and perspectives (Moore et al., 2012; Savin-Baden & Major, 2013). Thus, utilizing questionnaires and semi-structured interviews through open-ended questions is significant for obtaining rich data, analyzing the data meaningfully, and understanding the case comprehensively (Merriam, 1998).

Consequently, in this study, to conduct a case study effectively and investigate the topic deeply, the data for this study were collected from thirty-two prospective teachers through a questionnaire that included open-ended questions about various students' solutions. Thus, the aim was to answer the research questions with a wide range of data and to understand prospective teachers' attending, interpreting, and responding to diversity. In the second stage, semi-structured interviews were conducted with eight of them to obtain more in-depth information. Participants were selected for the interview based on the criteria of volunteering to participate and allocating an appropriate time for the interview. In addition, the participants' capacity to express their thoughts was also taken into consideration. In this context, their instructors' feedback was utilized to conclude that the participants expressed their thoughts more clearly and in detail. As a result, interviews were conducted with eight participants who met the mentioned criteria. Thus, after more in-depth responses in the interview from selected participants, it was ensured that the data provided a broad perspective and in-depth analysis that better supported the study's findings. Therefore, as an essential requirement of the case study, we had the opportunity to hear the prospective teachers' responses on how to notice students' solutions with complete clarity through the questionnaire, consisting of open-ended questions, and examine in-depth and verify their answers in the questionnaire through semi-structured interviews. In conclusion, the findings from both data collection methods were complementary and allowed us to comprehensively understand the prospective teachers' noticing of students' algebraic thinking.

Context and Participants

The current study concentrated on a fourth-year middle school mathematics teacher education (undergraduate) program at a public university in Ankara/Turkey. The program aims to train prospective teachers to gain competencies in improving students' problem-solving skills through critical thinking and teaching mathematics effectively by incorporating technology. The prospective teachers attend elementary mathematics education courses (e.g., Methods of Teaching Mathematics I-II and Nature of Mathematical Knowledge for Teaching), content courses (e.g., Calculus, Statistics, and Physics), and education sciences courses (e.g., Educational Psychology and Classroom Management). The prospective teachers complete most of the content courses in the first two years of this program, while taking education sciences courses and elementary mathematics education courses in the following years.

Participants were selected from one of the top universities in Türkiye through a purposeful sampling method to obtain rich data. Thirty-two prospective middle school mathematics teachers studying in their senior year participated in this study. In addition to many content and educational science courses, most participants completed Methods of Teaching Mathematics I-II and School Experience courses. In the Methods of Teaching Mathematics I-II courses, prospective teachers acquire knowledge on instructing students on mathematical topics and effective teaching methods. Moreover, they reflect on students' potential misconceptions while learning mathematics and discuss appropriate ways to address students' misconceptions.

Thus, the participants were familiar with students' possible conceptual confusion in algebra and algebraic thinking, as well as effective instructional strategies for teaching algebra to middle school students. In the School Experience course, on the other hand, they are given the chance to observe the actual classroom environment and lectures offered by mentor teachers and other prospective teachers. Moreover, as prospective teachers are responsible for giving lectures to an actual classroom within the scope of the School Experience course, the participants had the opportunity to practice teaching mathematics to students and receive feedback from their university instructor and mentor teacher in the middle school.

The content of Methods of Teaching Mathematics I-II and School Experience courses were not primarily designed to develop the prospective teachers' noticing skills. Instead, these courses aimed to enhance their knowledge about teaching mathematics topics effectively, centering on students' understanding and using this knowledge to teach any topic in the actual classroom as a part of their School Experience course. Since prospective teachers who took these courses can provide more extensive data on their noticing skills, participants were chosen from the prospective teachers who completed Methods of Teaching Mathematics I-II and School Experience courses.

Data Collection

This study's data was obtained through three different data collection tools: a questionnaire for 6th-grade students, a questionnaire for prospective teachers, and a semi-structured interview.

Questionnaire for 6th-Grade Students

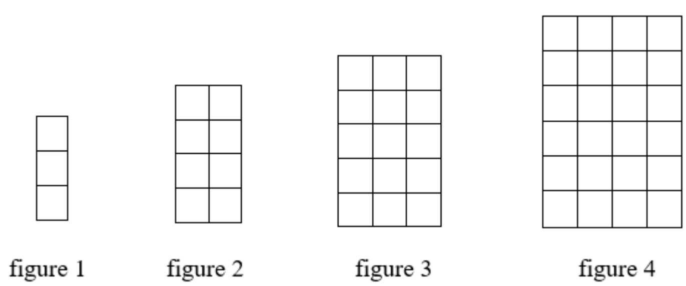
To examine the prospective teachers' professional noticing of students' algebraic thinking based on student works in detail, different students' solutions were needed. Thus, a questionnaire involving three open-ended questions regarding pattern generalization was applied to twenty 6^{th}-grade students to obtain these alternatives. As the objective, "Students should be able to express the rule of arithmetic sequences by using letters and find the desired term of sequences expressed in letters." The standard 6.2.1.1 (MoNE, 2013) is in the 6th-grade mathematics curriculum, so it was determined that the questionnaire be asked of 6th-grade students. Additionally, to comprehensively investigate teachers' noticing of students' algebraic thinking, it was essential to gather solutions, including correct and incorrect steps, mathematically noteworthy details, and exhibiting variability. Thus, the questionnaire for 6th-grade students was administered to students with varying alternative solutions and algebraic thought processes, ensuring the collection of solutions that met these specific criteria. Consequently, this approach enabled alternative 6th-grade student solutions to have a deep evaluation of teachers' noticing of students' solutions.

Since professional noticing of children's mathematical thinking comprised three skills and the study's primary aim was to investigate the prospective middle school mathematics teachers' professional noticing of students' algebraic thinking under three dimensions in depth, the researchers deliberately zoomed in on one of the three questions. One of the criteria for selecting the question was whether it was solved both correctly and incorrectly by the 6th-grade students. Although three questions were related to pattern generalization, this study focused on near and far generalizations since making near and far generalizations was considered a springboard for writing the rule of a pattern (Radford, 2008). For this reason, Question 1 (see Figure 1) was selected to examine prospective teachers' professional noticing in detail.

Figure 1

Question 1 (Radford, 2000)

The first four steps are given in the picture below. The rules of the 5^{th} step and other next steps in the pattern are the same as the rules in the first four steps. According to these steps, find the number of squares in the 25^{th} step. While finding the result, please draw a table and write the algebraic expression.



Questionnaire for Prospective Teachers

After applying the questionnaire to the students, one incorrect (Figure 2) and one correct (Figure 3) student solution was selected in accordance with the aim of this study. The reasons for selecting these solutions were that correct and incorrect solutions had different mathematical nuances to assess the prospective teachers' noticing skills (Jacobs et al., 2010), and these solutions reflected students' alternative thinking, which were worthy of noticing. The students' solutions are represented in the following figures:

Figure 2

Student A's Solution (Incorrect)

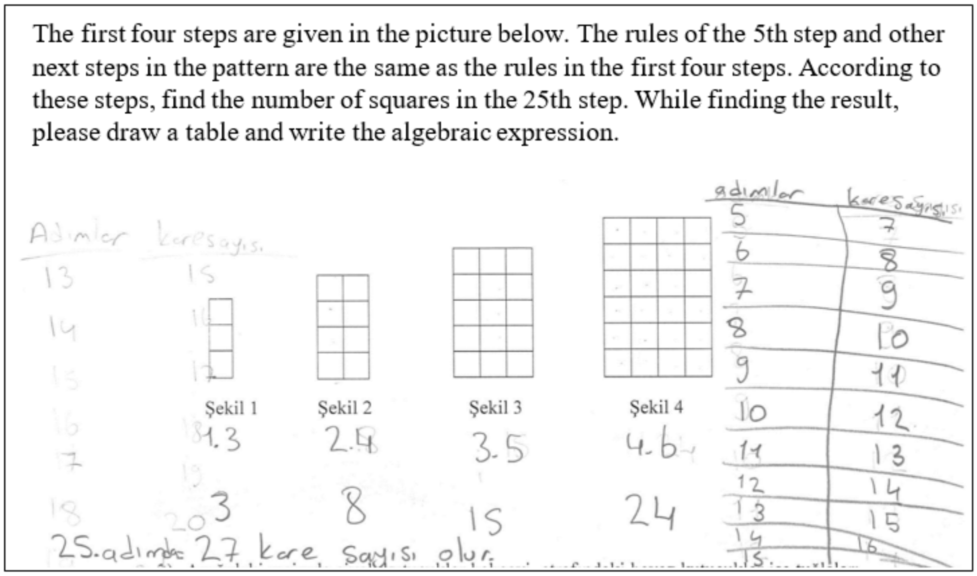
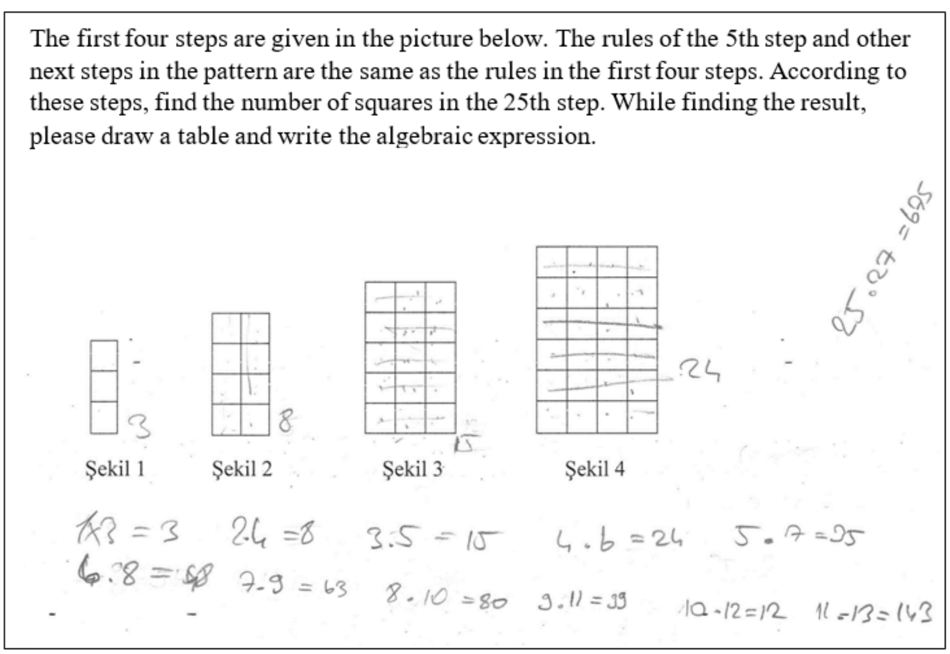


Figure 3

Student B's Solution (Correct)



The questionnaire involving three prompts, initially proposed by Jacobs et al. (2010), was implemented on thirty-two prospective teachers to investigate their skills of attending, interpreting, and deciding how to respond in relation to two students' solutions:

(1) "Please explain in detail what you think each child did in response to this problem.
(2) Please explain what you learned about these children's understanding.
(3) Pretend that you are the teacher of these children. What problem or problems might you pose next?" (Jacobs et al., 2010, 178-179).

Semi-structured interview

Semi-structured interviews offered a flexible structure, allowing participants to freely express their ideas while enabling in-depth exploration of specific issues of the research (Merriam, 1998). For this reason, this data collection tool was preferred to allow participants to express their responses in more detail and to seek answers to the research questions from a broader perspective after implementing the questionnaire. Eight participants were carefully selected for these interviews after implementing the questionnaire. Eight participants who volunteered, had time to participate in the interview, and could express their thoughts comfortably were selected, and an in-depth examination was made through interviews.

Necessary permissions were taken from the Human Subjects and Ethics Committee at the institution where the questionnaire and interviews were applied. Prior to collecting the data, information regarding the study was explained to each participant, and a consent form was taken from volunteer participants. Afterward, the researchers ensured that their personal details, responses, and video recordings would be kept confidential. Finally, a comfortable classroom environment was provided for the participants to answer the questionnaire and conduct interviews.

Data Analysis

In this study, a questionnaire was administered to thirty-two prospective teachers, and interviews were conducted with only eight of them. In data analysis, the responses provided in the questionnaire were primarily utilized. On the other hand, the responses of the prospective teachers, who both answered the questionnaire and were interviewed, were analyzed by considering the two data collection sources. Given that the responses of the prospective teachers who both answered the questionnaire and were interviewed were found to be parallel, their data was evaluated overall by considering the responses provided by both data collection tools. Therefore, some prospective teachers' responses given as examples in the finding sections were excerpted from a questionnaire, and some of them were taken from the interviews.

Data were analyzed according to the dimensions of the Professional Noticing of Children's Mathematical Thinking framework developed by Jacobs et al. (2010). As categories in this framework were insufficient to cover all the data of the present study, new categories were added, and some categories were split into subcategories based on the similarities and differences of the participants' responses. Two mathematics educators specializing in teacher noticing coded the data as co-coders to ensure inter-reliability. The co-coders' and the researchers' codes were compared to identify similarities and differences. Interrater reliability was determined at approximately 93% using the formula outlined by Miles and Huberman (1994). After another discussion about the discrepancies, the required adjustments were made, and ultimately agreement was reached. Consequently, two more categories – emerging evidence and limited evidence – were added to the dimension of attending, and one more category – emerging evidence – was added to the dimension of interpreting. In this way, the two dimensions of teacher noticing, attending and interpreting, could be investigated in greater detail by classifying them under four categories*: robust evidence, emerging evidence, limited evidence,* and *lack of evidence.* On the other hand, in this study, when the relevant data was analyzed, it was observed that prospective teachers either asked questions to develop and extend students' existing understanding or they asked structurally similar questions that were repetitive in nature that were unrelated to the student's current understanding. Prospective teachers' responses forced the researchers to categorize the third component of teacher noticing differently than Jacobs et al. (2010). Therefore, in order to reveal the characteristics of prospective teachers' responses better, the ability to decide how to respond was categorized under three sub-headings: *extending/supporting students' algebraic thinking, reinforcing procedural understanding,* and *providing a general response.* The findings section of the study contained more comprehensive information on these categories and the findings associated with them.

Findings

The findings of this study were presented under three dimensions: attending to students' solutions, interpreting students' algebraic thinking, and deciding how to respond based on the students' algebraic thinking.

Attending to Students' Solutions

This section presents the findings to answer the first research question related to prospective middle school mathematics teachers' attending to students correct and incorrect solutions of pattern generalization. In Jacobs et al.'s (2010) framework, the first component of professional teacher noticing, attending to students' solutions, comprises two categories: evidence of attending and lack of evidence of attending. However, this limited binary structure needed to be revised to adequately reflect the subtle differences in prospective teachers' attending in the current study, which hindered the in-depth analysis of the findings. Consequently, a four-category rating system was created, incorporating two new categories considering the typical characteristics of participants' responses. These additional categories allowed for a more detailed description of the different levels of attending to students' solutions by explaining the transitions in more detail. The properties of the categories related to the dimension of attending and the frequency of prospective teachers' responses are illustrated in Table 1.

Table 1

Details of the Dimension of Attending to Students' Solutions and the Frequency of Each Category

	Attending to Students' Solutions	Frequency
Student A Solution (incorrect)	*Robust Evidence of Attention to Students' Solution* Correctly identifying both how the student finds the number of squares in the first four steps and the student's mistake in creating the table.	17 (53.13%)
	Emerging Evidence of Attention to Students' Solution Correctly identifying how the student finds the number of squares in the first four steps, but the student's mistake in creating the table is missing.	11 (34.38%)
	Limited Evidence of Attention to Students' Solution Correctly identifying the student's mistake, but the explanation of the solution is not in detail.	3 (9.37%)
	Lack of Evidence of Attention to Students' Solution Describing the solution as correct.	1 (3.13%)

	Attending to Students' Solutions	Frequency
Student B Solution (correct)	*Robust Evidence of Attention to Students' Solution* Correctly identifying how the student finds the number of squares in the first four steps and finds the 25th figure.	16 (50%)
	Emerging Evidence of Attention to Students' Solution Correctly identifying how the student finds the number of squares in the first four steps but how the student concludes the solution is missing.	6 (18.75%)
	Limited Evidence of Attention to Students' Solution Correctly identifying student's result but the explanation of the solution is not in detail.	7 (21.88%)
	Lack of Evidence of Attention to Students' Solution Describing the solution as incorrect.	3 (9.37%)

Robust Evidence

More than half of the prospective teachers provided robust evidence to attend to student A's solution (53.13%) and student B's solution (50%), as they described all important mathematical details of the students' solutions. For instance, PT 2's explanation of student A's solution, taken from the questionnaire, was as follows:

> Wrong. In each figure, the student multiplied the number of rows and the number of squares in each row in that figure. When s/he was solving the 5th step, s/he wrote the number of rows in the 5th step instead of writing the total squares in that step. In other words, s/he started the solution with correct reasoning, but when s/he transferred the information to the table, s/he wrongly continued it. S/he continued with the 25th step and said that there were 27 squares in the 25th step since the difference between the number of steps and the number of rows in that step was 2.

PT 2 identified student A's solution as calculating the number of squares in each step by multiplying the number of columns and the number of rows. PT 2 also recognized student A's mistake in creating a table, which led to the incorrect result.

Emerging Evidence

While eleven prospective teachers (34.38%) attended to student A's solution by providing emerging evidence, six of them (18.75%) provided emerging evidence to attend to student B's solution, giving descriptions consisting of mathematically important details but not capturing all the details of the student solutions. PT 9's attending to student A's solution in the questionnaire was presented in the following way:

> The student realized that the number of rows in each step was two more than the number of steps, and s/he concluded his/her solution by stating that there were 27 squares in the 25th step. Student A's solution is wrong because 27 is not the number of squares in the 25th step; actually, it is the number of rows.

PT 9 *described how student A built the relationship* between the number of steps and the number of columns, stating that the student added two to 25. However, PT 9 did *not pay attention to student A's mistake* in transforming knowledge to the table.

Limited Evidence

Three prospective teachers (9.37%) attended to student A's solution, while seven of them (21.88%) attended to student B's solution by providing limited evidence because their explanation included a general description of the students' solutions and did not provide specificities about them. For instance, PT 24's description of student B's solution in the questionnaire illustrated this point:

> Here, the student was able to capture the pattern between the number of steps and the number of rows and reached the correct result, but the student found the solution after many steps.

As the quotation clearly demonstrated, PT 24 provided *a general description* of student B's solution by recognizing the relationship in the pattern.

Lack of Evidence

One prospective teacher's description of student A's solution (3.13%) and three prospective teachers' description of student B's solution (9.37%) were defined as lack of evidence because they either misrecognized or made irrelevant comments on students' thinking. PT 19's explanation related to student B's solution proved this to be true:

> The student's solution is correct. He understood the pattern and expressed it algebraically. He applied the pattern of n. n + 2 to 25^{th} step.

Radford (2008) stated that pattern generalization consisted of three stages: near generalization, far generalization, and writing the rule of pattern. The student B noticed the relationship in the pattern and wrote the 25th step of the pattern based on this relationship. Although student B made a far generalization, he was not able to formulate the rule of the pattern using algebraic expression. Attending is a skill about how the student solves the problem and what he does during the solution phase (Jacobs et al., 2010). Despite the definition of attending, the pre-service teacher described what the student should have done instead of elaborating on the student's current solution. In other words, although student B did not express the pattern algebraically, PT 19 provided the wrong evidence, stating that student B expressed the pattern algebraically. For this reason, PT's explanation was coded as lack of evidence.

Interpreting Students' Algebraic Thinking

This section presents the findings to answer the second research question about prospective middle school mathematics teachers' interpreting of students' algebraic thinking based on students correct and incorrect solutions within the context of pattern generalization. According to Jacobs et al.'s (2010) framework, the second component of professional teacher noticing, which is interpreting students' algebraic thinking, is coded under three categories: robust evidence, limited evidence, and lack of evidence. However, in this study, some participants' responses did not correspond to robust or limited evidence characteristics. Thus, there was a need to add one category, which is named emerging evidence, between robust and limited evidence. Thus, this newly added category describes responses that are not perfect enough to be considered "robust evidence" but perform above "limited evidence." Specifically, *emerging evidence* includes responses in which only **one** of the two expected aspects—either *the correct interpretation of the student's recognition of the relationship* or *the identification of the student's mistake*—is accurately addressed. This category recognizes a partial but meaningful level of interpreting students' algebraic thinking that exceeds l*imited evidence yet* does not meet the full expectations of r*obust evidence*. This revision made it possible to reveal the differences in prospective teachers' interpreting and provide more comprehensive answers to the research questions. The characteristics of the categories related to the dimension of interpreting and the frequency of prospective teachers' responses are displayed in Table 2.

Table 2

Details of the Dimension of Interpreting Students' Algebraic Thinking and the Frequency of Each Category

	Interpreting Students' Algebraic Thinking	Frequency
Student A Solution (incorrect)	*Robust Evidence of Interpreting Students' Algebraic Thinking*	
	Correctly interpreting both the student's exploration of the relationship between the number of squares and the number of rows and columns, and the student's mistake in the generalization of this relationship.	6 (18.75%)
	Emerging Evidence of Interpreting Students' Algebraic Thinking	
	Correctly interpreting either the student's exploration of the relationship between the number of squares and the number of rows and columns or the student's mistake in the generalization of this relationship.	6 (18.75%)
	Limited Evidence of Interpreting Students' Algebraic Thinking	
	Correctly interpreting only the student's incomprehension of the pattern generalization, but the interpretation of the student's algebraic thinking is not in detail.	11 (34.38%)
	Lack of Evidence of Interpreting Students' Algebraic Thinking	
	Making an incorrect or irrelevant interpretation of the student's algebraic thinking.	8 (25%)
	No answers	1 (3.13%)
Student B Solution (correct)	*Robust Evidence of Interpreting Students' Algebraic Thinking*	
	Correctly interpreting the student's exploration of the relationship between the number of squares and the number of rows and columns and the student's generalization of this relationship.	10 (31.25%)
	Emerging Evidence of Interpreting Students' Algebraic Thinking	
	Correctly interpreting either the student's exploration of the relationship between the number of squares and the number of rows and columns or the student's generalization of this relationship.	11 (34.38%)
	Limited Evidence of Interpreting Students' Algebraic Thinking	
	Correctly interpreting only the student's comprehension of the pattern generalization, but the interpretation of the student's algebraic thinking is not in detail.	6 (18.75%)
	Lack of Evidence of Interpreting Students' Algebraic Thinking	
	Making an incorrect or irrelevant interpretation of a student's algebraic thinking.	3 (9.37%)
	No answers	2 (6.26%)

Robust Evidence

Six prospective teachers (18.75%) managed to interpret student A's algebraic thinking with robust evidence, whereas ten of them (31.25%) provided robust evidence to interpret student B's algebraic thinking. PT 7's interpretation of student B's algebraic thinking excerpted from the interview transcript was as follows:

Researcher: What can you say about the student's understanding?
PT 7: Pattern… wait a minute… I looked at the pattern of multiplications. Pattern is actually…

> S/he recognized that the pattern of the number of rows and the number of columns increased one by one in each step and the difference between the number of rows and columns is two in each step.
> **Researcher**: Okay. You said that the student explored the pattern in the questionnaire. How did you make such an inference?
> **PT 7:** The first reason was that the student solved the problem correctly. The second reason was that the student did not write the solution step by step until the 25th step. In other words, after the 11th step, s/he explored the pattern and found it without writing step by step all the steps between. The primary reason for exploring the pattern is to find the result of the far step. Actually, s/he succeeded in here.

PT 7 analyzed that student B properly both *recognized the relationship* between the number of rows and columns, and the number of squares, and then s/he *correctly discovered the pattern*. This response was categorized as *robust evidence* because PT 7 accurately addressed both key aspects: interpreting *the student's recognition of the relationship* and *identifying the student's reasoning in generalizing the pattern*.

Emerging Evidence

Similar to interpreting with robust evidence, six prospective teachers' interpretations of student A's algebraic thinking (18.75%) and eleven prospective teachers' interpretations of student B's algebraic thinking (34.38%) were categorized as emerging evidence. PT 32's interpretation of student B's algebraic thinking in the questionnaire exemplified this claim:

> He knows that he must multiply the [the number of] rows and columns to find the number of squares. Also, he correctly forms a relationship between the number of rows in steps. But he couldn't reach the result. I think there is a lack of attention.

Although PT 32 correctly analyzed that student B could *recognize the relationship* between the number of squares and the number of rows and columns, PT 32 *could not identify the student's mistake* while filling in the table. Therefore, this response was categorized as *emerging evidence* because only one of the two required aspects—*recognizing the relationship*—was accurately interpreted. The failure to *identify the student's mistake* distinguishes it from *robust evidence*, which necessitates the correct interpretation of both elements.

Limited Evidence

Eleven prospective teachers (34.38%) for student A and six of them (18.75%) for student B were able to state whether the student could comprehend the pattern generalization or not, but they failed to refer to the specific points regarding the student's algebraic thinking. For example, PT 3's interpretation of student B's algebraic thinking in the questionnaire portrayed limited evidence:

> This student actually calculated by writing up to figure 11. I think he found the other steps by counting without writing. That's why he set out the figures rather than the concept.

PT 3 only emphasized that the student could solve the problem by focusing on figures, and the prospective teacher could *not provide any details* about the student's algebraic thinking.

Lack of Evidence

Eight prospective teachers (25%) presented misinterpretation and irrelevant comments on student A's algebraic thinking, whereas three of them (9.37%) misinterpreted student B's algebraic thinking and made irrelevant comments on student B's algebraic thinking. PT 19's interpretation of student A's algebraic thinking in the questionnaire indicated a lack of evidence:

> S/he is unable to make sense of the drawing table. S/he made an error while writing the information related to the question on the table. S/he used the table as s/he saw from a friend or from the previous lessons.

PT 19's interpretation *did not include any specific comments* such as the details about the student's recognition of the relationship, their discovery of the pattern, or their generalization. Moreover, this interpretation *was irrelevant to student A's thinking.*

Deciding How to Respond on the Basis of Students' Algebraic Thinking

This section presents the findings to answer the third research question related to the nature of the decisions that prospective middle school mathematics teachers make to respond based on students' correct and incorrect algebraic thinking within the context of pattern generalization. According to Jacobs et al.'s (2010) framework, the third component of professional teacher noticing, deciding how to respond, includes three categories: robust evidence, limited evidence, and lack of evidence. However, in the current study, prospective teachers responded to students by extending/supporting their thinking, reinforcing procedural understanding, or providing a general response. For this reason, it was determined that participants' responses were categorized based on the nature of their responses instead of as robust, limited and lack of evidence. The properties of each category in relation to the dimension of deciding how to respond and the frequency of prospective teachers' responses are presented in Table 3.

Table 3

Details of the Dimension of Deciding How to Respond on the Basis of Students' Algebraic Thinking and the Frequency of Each Category

	Deciding How to Respond to Students	Frequency
Student A Solution (incorrect)	*Extending/Supporting Students' Algebraic Thinking* Supporting student's existing algebraic thinking by asking a question to make the student recognize his/her mistakes/misconceptions.	22 (68.75%)
	Reinforcing Procedural Understanding Asking a similar question with minimal variation (e.g., changing numbers) without supporting the student's algebraic thinking.	1 (3.13%)
	Providing a General Response Asking the question independent from the student's algebraic thinking. Suggesting direct instruction.	8 (25%)
	No answers	1 (3.13%)

	Deciding How to Respond to Students	Frequency
Student B Solution (correct)	*Extending/Supporting Students' Algebraic Thinking* Extending the student's existing algebraic thinking through new questions.	7 (21.88%)
	Reinforcing Procedural Understanding Asking a similar question with minimal variation (e.g., changing numbers) in order to reinforce the student's previously acquired knowledge without extending or deepening their algebraic thinking.	7 (21.88%)
	Providing a General Response Asking the question independent from the student's algebraic thinking. Suggesting direct instruction.	17 (53.13%)
	No answers	1 (3.13%)

Extending/Supporting Students' Algebraic Thinking

A vast majority of the prospective teachers (68.75%) supported the algebraic thinking of student A, who had misconceptions/mistakes, making the student recognize his/her mistakes with follow-up questions. It was surprising that seven of them (21.88%) could extend the algebraic thinking of student B through new questions after s/he solved the problem correctly. For instance, to respond to the student A, PT 7 uttered the following remarks:

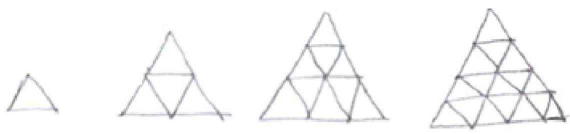
> (1) You said there were 24 squares in the 4th step, and there were 27 squares in the 25th step. How many shapes were there between figure 4 and figure 5? Do you think that the difference between them is three makes sense?
> (2) Can you draw figure 5? Then can you compare the number you found in figure 5 and figure 24?
> (3) (I asked the student to make an estimation.) What has changed in the rows and columns after each step? If the number of rows and columns increases by one, at least how many more squares will there be in figure 5 than figure 4? Can you make an estimation about the number of squares in figure 5? If the number of rows and columns increases by one, what is the difference in number between the number of squares in figure 5 and the number of steps in figure 4? Can you estimate the number of squares in figure 5?

PT 7, in his/her response, *tried to make student A realize his/her mistake via different questions*. In the first question, PT 7 aimed to make student A recognize the fact that there were 27 squares in the 25th step, which was not correct, while the number of squares in the 4th step was 24. PT 7 asked the second question to make student A realize that there were 35 squares in the 5th step, which meant there were more squares than 27. PT 7 supported the student in generalizing the pattern via the third question. Thus, PT 7 supported student A's algebraic thinking.

Reinforcing Procedural Understanding

Only one prospective teacher (3.13%) asked a similar question to student A, who had an incorrect solution without supporting his/her algebraic thinking, whereas seven prospective teachers (21.88%) asked a similar question to student B, who had a correct solution without being able to reinforce his/her algebraic thinking. For instance, to respond to the student B, PT 4 suggested such a question:

"Find the number of triangles in the 25th step of the figure below."



PT 4's question is organized similarly to the question asked on the questionnaire, and it does not force the student to develop a new conceptual understanding and is merely an exercise to develop previously acquired skills and procedures. For this reason, rather than extending student B's thinking, this question encourages student B to consolidate their skills through procedural learning and to apply a particular process more efficiently. For this reason, PT 4's question that was offered to student B is an example of reinforcing procedural understanding.

Providing a General Response

Eight prospective teachers (25%) for student A and more than half of them (53.13%) for student B suggested direct instruction or asked questions that were irrelevant to the student's algebraic thinking. For example, to respond to the student B, PT 18 suggested the following remark:

> Even, student B solved the question correctly. I asked about a similar problem involving different patterns.

PT 18 did *not take student B's algebraic thinking into consideration* and only explained the type of question s/he wanted to direct.

Discussion

Drawing primarily on the "Professional Noticing of Children's Mathematical Thinking" framework suggested by Jacobs et al. (2010), this study aimed to examine prospective middle school mathematics teachers' noticing of students' algebraic thinking on their correct and incorrect responses within the context of pattern generalization. In line with this framework, the findings of the present study were separately discussed under three dimensions: attending to students' solutions, interpreting students' algebraic thinking, and deciding how to respond based on their algebraic thinking.

Attending to Students' Solutions

In this section, the findings related to the first research question about prospective middle school mathematics teachers' attending to students correct and incorrect solutions of pattern generalization were discussed. The findings of the study revealed that more than half of the prospective teachers participating in this study provided robust evidence of attending to students' both correct and incorrect solutions in the context of pattern generalization. The main factor influencing teachers' success in attending might stem from the nature of issues focusing on pattern generalization. As indicated earlier, a pattern generalization process is composed of three stages: (1) near-term generalization, (2) far-term generalization, and (3) writing a rule of pattern (Radford, 2008). To generalize a pattern, students inevitably engage in reasoning in each stage and address the problem following a step-by-step approach (Jurdak & El Mouhayar, 2014; Lannin et al., 2006). Therefore, asking students for a step-by-step solution can aid prospective teachers in identifying how students find a pattern and at which step they make mistakes. Another reason contributing to their success might be related to the properties of the attending skill. Jacobs et al. (2010) defined this skill as the ability to identify how students perform the operations, which tools or figures they use, and how they employ them to represent the key issues presented in the problem. Therefore, the ability to attend to students' responses does not require teachers to identify the conceptual aspects of students' strategies; instead, it requires recognizing the procedural aspects of the strategies implemented. In this respect, this study validated the previous research, which reported that attending, among the three skills, was the one that teachers could apply most easily (LaRochelle, 2018; Sánchez-Matamoros et al., 2019).

Moreover, adding two new categories to the existing categorizations in Jacobs et al.'s (2010) framework provided an opportunity to reveal more clearly the differences and transitions between prospective teachers' attending to students' solutions. The extended categories presented codes and ideas for the researchers to investigate teachers' noticing by using students' incorrect solutions, as well as the correct solutions. Thus, this revision in Jacobs et al.'s (2010) framework contributes to a more meaningful interpretation of the findings related to prospective teachers' attending and more comprehensive answers to the first research question by providing a finer distinction in the analysis. Thus, other researchers can benefit from these categories to investigate teachers' attending to students' solutions within other mathematics contexts with participants from different contexts and backgrounds.

In this section, the findings related to the second research question about prospective middle school mathematics teachers' interpreting of students' algebraic thinking based on students' solutions within the context of pattern generalization were discussed. Similar to attending to students' solutions, it was expected that the step-by-step solution arising from the nature of the pattern generalization process would facilitate teachers' interpretation of students' algebraic thinking. However, it was surprising to find out that the prospective teachers had difficulty in making sense of the students' solutions and interpreting their algebraic thinking. In line with this striking finding, Zapatera and Callejo (2013) found out that some prospective teachers had trouble interpreting students' mathematical thinking in the process of pattern generalization. Another significant finding related to the interpreting skill was that the prospective teachers' success in interpreting students' algebraic thinking largely depended on the correctness of students' strategies. More specifically, it was found that the prospective teachers had more difficulty in interpreting students' algebraic thinking with an incorrect solution than a correct one. Although previous studies pinpointed that the attending skill was the basis of interpretation (Jacobs et al., 2010; LaRochelle, 2018), this result of the study showed that providing robust evidence of attending did not necessarily guarantee robust evidence of interpretation when students' solutions were incorrect.

Attending to students' incorrect solutions requires explaining the details of the correct steps followed, if they exist, and identifying in which step students make the mistakes. However, interpreting the algebraic thinking of students who solve the problem incorrectly requires interpreting the reasoning behind their mistakes. For example, teachers have to elaborate on whether students' misunderstandings are a result of their misrecognition of near generalization or far-term generalization. However, the prospective teachers in this study were not able to explain why the student made the mistakes, although they succeeded in attending to the mistakes. In this sense, it is far from controversial to claim that prospective teachers who could not interpret students' incorrect solutions might not have enough knowledge about students' mistakes/misconceptions. In other words, they might have limited "knowledge of content and students" (KCS), a body of knowledge indicating whether teachers are "be[ing] able to hear and interpret students' emerging and incomplete thinking" (Ball et al., 2008, p. 402).

The extension of Jacobs et al.'s (2010) framework and the addition of a transitional category between "robust evidence" and "limited evidence" in this dimension allows for a more detailed evaluation of the analysis by revealing more clearly the subtle differences in the levels of interpreting to students' algebraic thinking. In particular, the added category of "emerging evidence" allows for a more precise classification of the data and contributes to a more realistic and reliable reflection of the findings. Thus, the responses to the second research question became more comprehensive and nuanced. Finally, the extended categories presented codes and ideas for researchers to investigate teachers' interpreting students' algebraic thinking based on both students' incorrect solutions and the correct solutions. In this regard, these categories to investigate teachers' interpretation of students' thinking within other mathematics contexts with participants from different contexts and backgrounds can be used by other researchers.

Deciding How to Respond on the Basis of Students' Algebraic Thinking

In this section, the findings related to the third research question about the nature of the decisions that prospective middle school mathematics teachers make to respond based on students correct and incorrect algebraic thinking within the context of pattern generalization were discussed. The most striking finding of this study was that the majority of the prospective teachers provided answers that would support the algebraic reasoning of the students, although most of them were unable to interpret the algebraic thinking of the students with incorrect solution. In other words, the teachers aimed to make the students recognize their misconceptions through follow-up questions. On the other hand, collaborating with the results of the previous studies (Crespo, 2002; Milewski & Strickland, 2016), instead of asking divergent questions to the students who solved the problem correctly to expand their algebraic reasoning, most of the prospective teachers gave general responses that were not directly related to the students' thinking. As a consequence, it would be worthwhile to note that the prospective teachers' responses to the students varied according to the accuracy of the students' solutions. To be more specific, the teachers directed more efficient questions to the student with an incorrect solution than the one with the correct solution. These findings allowed us to argue that the prospective teachers having expertise in dealing with students' incorrect thinking might have prior knowledge about students' potential misconceptions, alternative teaching methods for addressing students' misconceptions, and the types of questions that might be asked to make students recognize their mistakes/misconceptions (Milewski & Strickland, 2016). Seen from this perspective, this result suggested that the prospective teachers might have been qualified enough to handle students' misconceptions through their "knowledge of content and teaching" (KCT), indicating that they were familiar with effective teaching strategies and appropriate examples/demonstrations for the teaching of the subject (Ball et al., 2008).

With regard to responding to the student with the correct solution, the prospective teachers may have considered that the task was completed, and thus, they may not have imagined that students' algebraic thinking could be expanded by asking challenging questions. Along with this, they may also have believed that praise was a sufficient response for the students with correct solutions, which stood in parallel with the results of previous research (Crespo, 2002; Milewski & Strickland, 2016). Furthermore, asking problems to extend students' existing knowledge might be challenging for some teachers, as undertaking such a task might require KCT (Jacobs et al., 2010). To explicate further students' correct solutions, teachers should familiarize themselves with effective teaching methods, such as representations and questions that will push the student one step further, which, in a sense, refers to KCT (Ball et al., 2008). Consequently, the differences between the nature of teachers' responses to the students' in/correct solution demonstrated that the prospective teachers had extensive KCT to address the students' incorrect solution, whereas their KCT was relatively limited in terms of explicating on the students' correct understanding.

In addition to KCT, another possible explanation for why prospective teachers did not extend students' correct solutions may relate to their Horizon Content Knowledge (HCK). HCK is defined by Ball et al. (2008) as "an awareness of how mathematical topics are related over the span of mathematics included in the curriculum" (p. 403). This type of knowledge enables teachers to make informed decisions about how to frame mathematical ideas in ways that anticipate future learning and connect current concepts to more advanced topics (Ball et al., 2008). From this perspective, the inability to expand on students' correct responses may stem from a limited awareness of how the student's current understanding could be deepened or linked to more sophisticated ideas appropriate to their grade level and curriculum. Thus, limitations in HCK may also have contributed to the nature of the prospective teachers' responses, particularly their missed opportunities to extend students' algebraic thinking.

Furthermore, the differences between prospective teachers' responses to the student with correct and incorrect solutions might be related to the content of the Methods of Teaching Mathematics I-II and School Experience courses. In Methods of Teaching Mathematics I-II courses, the prospective teachers may not have focused on how to deepen the understanding of students with correct solutions. Instead, they may mostly have dwelled on how to correct the understanding of students with incorrect solutions. Apart from that, while they were observing the teachers in the classroom as a part of the School Experience course, they may just have noticed students who made mistakes rather than those coming up with correct solutions. Therefore, it can be speculated that prospective teachers were more familiar with offering instructional intervention to students with incorrect solutions as a result of their courses. This could be one of the possible reasons why prospective teachers participating in the current study were far better at offering more effective questions to correct their understanding.

Moreover, the prospective teachers' deficiency in extending the algebraic thinking of the students with a correct solution might be caused by the nature of the pattern generalization process. The problems about pattern generalization are solved by employing a step-by-step method, namely near generalization, far generalization, and writing the rule of the pattern (Jurdak & El Mouhayar, 2014; Lannin et al., 2006). Therefore, it can be a compelling task for teachers to decide on a possible effective intervention with regard to each of these steps for students who offer correct solutions to the problem to extend their algebraic thinking.

Last but not least, the contribution of this study was the different categorization of the third dimension of teacher noticing from Jacobs et al.'s (2010) framework. In this dimension, prospective teachers' deciding how to respond was coded under three categories, which are extending/supporting students' algebraic thinking, reinforcing procedural understanding, and providing a general response instead of as robust, limited, and lack of evidence. This categorization gave an opportunity to examine prospective teachers' responses based on the nature of their responses, which makes this study more sensible. More importantly, it underlined teachers' next steps in terms of supporting and extending students' existing understanding. Furthermore, this modified categorization allowed for the evaluation of teachers' decisions on how to respond to students with both correct and incorrect solutions. To be more specific, prospective teachers' responses to students with correct and incorrect solutions in relation to pattern generalization were granted an opportunity to be discussed together, which in return gave the prospective teachers another perspective related to pattern generalization. Therefore, this categorization might be effective in examining teachers' decisions on responding within other mathematics contexts with participants from different contexts and backgrounds.

In short, although the prospective teachers could attend to students' both correct and incorrect solutions, they had difficulty in interpreting a student's incorrect solution and responding to the students who solved the problem correctly. To put it another way, while attending was an easily practiced skill for dealing with both correct and incorrect solutions, the correctness of students' solutions served as an important indicator of the prospective teachers' interpreting and responding skills. Although the prospective teachers had more difficulty in interpreting the student's incorrect solution than the correct solution, they were more successful in responding to the student who had an incomplete understanding or a misunderstanding in the context of pattern generalization. This finding showed some contradiction with previous research, as it did not completely verify the claim that "deciding how to respond based on children's understandings can occur only if teachers interpret children's understandings, and these interpretations can be made only if teachers attend to the details of children's strategies" (Jacobs et al., 2010, p. 197). More specifically, the findings of the current study showed that although the prospective teachers had the ability to attend to and interpret the students' correct understanding, they found it challenging to respond to the students who had correct reasoning. However, the same relationship between these three skills could not be found for students with incorrect understanding. That is, the prospective teachers had the ability to provide a high level of response to the students with incorrect understanding, though they could not interpret students' incorrect understanding. Based on these findings, this study made significant contributions to the literature on mathematics education by reporting that deciding how to respond to students' incorrect understandings did not require a high level of interpretation of their incorrect understandings.

When considering the limitations of this study, it is noteworthy that the prospective teachers' noticing has been examined solely through two students' solutions. Consequently, there is a need for a more comprehensive investigation in future studies, encompassing a broader spectrum of algebraic topics, and incorporating a diverse set of incorrect and correct student solutions.

Additionally, further studies could be conducted to investigate prospective teachers' noticing of algebraic thinking in other countries by utilizing the categorization presented in the current study. Cross-cultural studies vis-à-vis prospective teachers' noticing of algebraic thinking might be carried out to evaluate whether a cultural dimension of an educational context is an indicative factor for the shape of teachers' noticing. Moreover, investigating the relationship between teacher knowledge and teacher noticing from the point of students' both correct and incorrect understanding within the context of different mathematical domains would be significant as a recommendation for a future study.

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References

Ball, D. L., Thames, M. H., & Phelps, G. (2008). Content knowledge for teaching: What makes it special? *Journal of Teacher Education, 59*(5), 389–407. http://dx.doi.org/10.1177/0022487108324554

Blanton, M. L., & Kaput, J. J. (2005). Characterizing a classroom practice that promotes algebraic reasoning. *Journal for Research in Mathematics Education, 36*(5), 412–446.

Blömeke, S., Gustafsson, J.-E., & Shavelson, R. (2015). Beyond dichotomies: Competence viewed as a continuum. *Zeitschrift für Psychologie*, *223* (1), 3–13. http://dx.doi.org/10.1027/2151-2604/a000194

Carraher, D. W., & Schliemann, A. D. (2007). Early algebra and algebraic reasoning. In F. K. Lester, Jr., (Ed.), *Second handbook of research on mathematics teaching and learning (*Vol. II, pp. 669-705). Information Age Publishing.

Chick, H. L., Baker, M., Pham, T., & Cheng, H. (2006). Aspects of teachers' pedagogical content knowledge for decimals. In J. Novotna, H. Moraova, M. Kraka & N. Stehlikova (Eds.), *Proceedings of the 30th Conference of the International Group for the Psychology of Mathematics Education* (Vol. 2, pp. 297–304). PME.

Crespo, S. (2002). Praising and correcting: Prospective teachers investigate their teacherly talk. *Teaching and Teacher Education, 18*(6), 739–758. http://dx.doi.org/10.1016/S0742-051X(02)00031-8

Creswell, J. W. (2007). *Qualitative inquiry and research design: Choosing among five approaches* (2nd ed.). Sage Publications, Inc.

Curry, L. A. (2004). The effects of self-explanations of correct and incorrect solutions on algebra problem-solving performance. In K. Forbus, D. Gentner, & T. Regier (Eds). *Proceedings of the Annual Meeting of the Cognitive Science Society* (Vol. 26, No. 26). Erlbaum.

Copur-Gencturk, Y., & Rodrigues, J. (2021). Content-specific noticing: A large-scale survey of mathematics teachers' noticing. *Teaching and Teacher Education*, *101*, 103320. http://dx.doi.org/10.1016/j.tate.2021.103320

Franke, M. L., Carpenter, T. P., Levi, L., & Fennema, E. (2001). Capturing teachers' generative change: A follow-up study of professional development in mathematics. *American Educational Research Journal*, *38*(3), 653-689. http://dx.doi.org/10.3102/00028312038003653

Goodwin, C. (1994). Professional vision. *American Anthropologist, 96*(3), 606–633. http://dx.doi.org/10.1525/aa.1994.96.3.02a00100

Girit-Yildiz, D., Osmanoglu, A., & Gundogdu Alayli, F. (2022). Providing a video-case-based professional development environment for prospective mathematics teachers to notice students' misconceptions in measurement. *Journal of Mathematics Teacher Education*, *26,* 179-209. http://dx.doi.org/10.1007/s10857-021-09525-0

Grossman, P., Compton, C., Igra, D., Ronfeldt, M., Shahan, E., & Williamson, P. W. (2009). Teaching practice: A cross professional perspective. *Teachers College Record*, *111*(9), 2055–2100. http://dx.doi.org/10.1177/016146810911100905

Holt, P., Mojica, G., & Confrey, J. (2013). Learning trajectories in teacher education: Supporting teachers' understandings of students' mathematical thinking. *Journal of Mathematical Behavior, 32,* 103–121. http://dx.doi.org/10.1016/j.jmathb.2012.12.003

Ivars, P., Fernández, C., & Llinares, S. (2020). A learning trajectory as a scaffold for pre-service teachers' noticing of students' mathematical understanding. *International Journal of Science and Mathematics Education, 18*(3), 529–548. https://doi.org/10.1007/s10763-019-09966-w

Jacobs, V. R., & Ambrose, R. C. (2008). Making the most of story problems. *Teaching Children Mathematics, 15*(5), 260–266. http://dx.doi.org/10.5951/TCM.15.5.0260

Jacobs, V. R., & Empson, S. B. (2016). Responding to children's mathematical thinking in the moment: An emerging framework of teaching moves. *ZDM – Mathematics Education, 48*(1–2), 185–197. https://doi.org/10.1007/s11858-015-0717-0

Jacobs, V. R., Lamb, L. L., & Philipp, R. A. (2010). Professional noticing of children's mathematical thinking. *Journal for Research in Mathematics Education*, *41*(2) 169–202. http://dx.doi.org/10.5951/jresematheduc.41.2.0169

Jacobs, V. R., & Philipp, R. A. (2004). Supporting teacher learning: Mathematical thinking: Helping prospective and practicing teachers focus. *Teaching Children Mathematics, 11*(4), 194–201. http://dx.doi.org/10.5951/TCM.11.4.0194

Jurdak, M. E., & Mouhayar, R. R. (2014). Trends in the development of student level of reasoning in pattern generalization tasks across grade level. *Educational Studies in Mathematics, 85*(1), 75–92. http://dx.doi.org/10.1007/s10649-013-9494-2

Kaiser, G., Busse, A., Hoth, J., König, J., & Blömeke, S. (2015). About the complexities of video-based assessments: Theoretical and methodological approaches to overcoming shortcomings of research on teachers' competence. *International Journal of Science and Mathematics Education*, *13*(2), 369-387. http://dx.doi.org/10.1007/s10763-015-9616-7

Kaput, J. (1999). Teaching and learning a new algebra. In E. Fennama &T.Romberg (Eds.), *Mathematics classrooms that promote understanding* (pp.133–155). Mahwah, Erlbaum.

Kılıç, H., & Doğan, O. (2021). Preservice mathematics teachers' noticing in action and in reflection. *International Journal of Science and Mathematics Education*, *20*(2), 1–22. http://dx.doi.org/10.1007/s10763-020-10141-2

Kieran, C., & Chalouh, L. (1993). Prealgebra: The transition from arithmetic to algebra. In D. T. Owens (Ed.), *Research ideas for the classroom: Middle grades mathematics* (pp. 179-198). Macmillan.

Knuth, E. J., Alibali, M. W., McNeil, N. M., Weinberg, A., & Stephens, A. C. (2005). Middle school students' understanding of core algebraic concepts: Equality and variable. *ZDM – Mathematics Education, 37*(1), 68–76. https://doi.org/10.1007/BF02655899

Lannin, J. K., Barker, D. D., & Townsend, B. E. (2006). Recursive and explicit rules: How can we build student algebraic understanding? *The Journal of Mathematical Behavior, 25*(4), 299–317. http://dx.doi.org/10.1016/j.jmathb.2006.11.004

LaRochelle, R. M. (2018). *Secondary teachers' professional noticing of students' mathematical thinking*. [Doctoral dissertation, University of California San Diego] eScholarship.

LaRochelle, R., Nickerson, S. D., Lamb, L. C., Hawthorne, C., Philipp, R. A., & Ross, D. L. (2019). Secondary practicing teachers' professional noticing of students' thinking about pattern generalization. *Mathematics Teacher Education and Development, 21*(1), 4–27.

Lee, M. Y. (2019). The development of elementary pre-service teachers' professional noticing of students' thinking through adapted lesson study. *Asia-Pacific Journal of Teacher Education, 47*(4), 383–398. http://dx.doi.org/10.1080/1359866X.2019.1607253

Mason, J. (2011). Noticing: Roots and branches. In M. Sherin, V. Jacobs, & R. Philipp (Eds.), *Mathematics teacher noticing: Seeing through teachers' eyes* (pp. 65–80). Routledge.

Merriam, S. B. (1998). *Qualitative research and case study applications in education (Rev. ed.).* Jossey-Bass.

Miles, M. B., & Huberman, A. M. (1994). *Qualitative data analysis: An expanded source book*. Sage Publications.

Milewski, A., & Strickland, S. (2016). (Toward) Developing a common language for describing instructional practices of responding: A teacher-generated framework. *Mathematics Teacher Educator, 4*(2), 126–144. http://dx.doi.org/10.5951/mathteaceduc.4.2.0126

Milli Eğitim Bakanlığı [Ministry of National Education] (MoNE). (2013). *Ortaokul matematik dersi (5, 6, 7, ve 8. Sınıflar) öğretim programı* [Middle school mathematics curriculum grades 5 to 8]. Ankara, Türkiye: MEB.

Moore, T. S., Lapan, S. D., & Quartaroli, M. T. (2012). Case study research. In S. D. Lapan, M. T. Quartaroli, & F. Riemer (Eds.), *Qualitative research: An introduction to methods and design* (p.243-270). John Wiley & Sons.

Nickerson, S. D., Lamb, L., & LaRochelle, R. (2017). Challenges in measuring secondary mathematics teachers' professional noticing of students' mathematical thinking. In E. Schack, M. Fisher, & J. Wilhelm (Eds.), *Teacher noticing: Bridging and broadening perspectives, contexts, and frameworks* (pp. 381–398). Springer.

Radford, L. (2000). Signs and meanings in students' emergent algebraic thinking: A semiotic analysis. *Educational Studies in Mathematics, 42*(3), 237–268. http://dx.doi.org/10.1023/A:1017530828058

Radford, L. (2008). Iconicity and contraction: A semiotic investigation of forms of algebraic generalizations of patterns in different contexts. *ZDM, 40*(1), 83–96. http://dx.doi.org/10.1007/s11858-007-0061-0

Rakes, C. R., Valentine, J. C., McGatha, M. B., & Ronau, R. N. (2010). Methods of instructional improvement in algebra: A systematic review and meta-analysis. *Review of Educational Research, 80*(3), 372–400. https://doi.org/10.3102/0034654310374880

Savin-Baden, M., & Major, C. (2013). *Qualitative research: The essential guide to theory and practice.* Routledge.

Sánchez-Matamoros, G., Fernández, C., & Llinares, S. (2019). Relationships among prospective secondary mathematics teachers' skills of attending, interpreting and responding to students' understanding. *Educational Studies in Mathematics, 100*(4), 83-99. https://doi.org/10.1007/s10649-018-9855-y

Sfard, A. (1995). The development of algebra: Confronting historical and psychological perspectives. *Journal of Mathematical Behavior, 14*, 15–39. http://dx.doi.org/10.1016/0732-3123(95)90022-5

Shaughnessy, M., DeFino, R., Pfaff, E., & Blunk, M. (2021). I think I made a mistake: How do prospective teachers elicit the thinking of a student who has made a mistake?. *Journal of Mathematics Teacher Education*, *24*(4), 335–359. http://dx.doi.org/10.1007/s10857-020-09461-5

Stacey, K. (1989). Finding and using patterns in linear generalizing problems. *Educational Studies in Mathematics, 20*(2), 147–164.

Star, J., & Strickland, S. (2008). Learning to observe: Using video to improve preservice mathematics teachers' ability to notice. *Journal of Mathematics Teacher Education, 11*(2), 107–125. http://dx.doi.org/10.1007/s10857-007-9063-7

Stevens, R., & Hall, R. (1998). Disciplined perception: Learning to see in technoscience. In M. Lampert & M. L. Blunk (Eds.), *Talking mathematics in school: Studies of teaching and learning* (pp. 107–150). Cambridge University Press.

Swafford, J. O., & Langrall, C. W. (2000). Grade 6 students' preinstructional use of equations to describe and represent problem situations. *Journal for Research in Mathematics Education*, *31*(1), 89–112. http://dx.doi.org/10.2307/749821

Taylan, R. D. (2017). Characterizing a highly accomplished teacher's noticing of third-grade students' mathematical thinking. *Journal of Mathematics Teacher Education, 20*(3), 259-280. http://dx.doi.org/10.1007/s10857-015-9326-7

Tyminski, A. M., Simpson, A. J., Land, T. J., Drake, C., & Dede, E. (2021). Prospective elementary mathematics teachers' noticing of children' mathematics: A focus on extending moves. *Journal of Mathematics Teacher Education*, *24*(6), 533–561. http://dx.doi.org/10.1007/s10857-020-09472-2

van Es, E. A., & Sherin, M. G. (2002). Learning to notice: Scaffolding new teachers' interpretations of classroom interactions. *Journal of Information Technology and Teacher Education, 10*(4), 571–596.

van Es, E. A., & Sherin, M. G. (2021). Expanding on prior conceptualizations of teacher noticing. *ZDM*, *53*(1), 17–27. http://dx.doi.org/10.1007/s11858-020-01211-4

Walkoe, J. D. K. (2013). *Investigating teacher noticing of student algebraic thinking* (864781505). [Doctoral dissertation, Northwestern University]. Dissertation Abstracts International.

Zapatera, A., & Callejo, M. L. (2013). Pre-service primary teachers' noticing of students' generalization process. In A. Lindmeier & A. Heinze (Eds.), *Proceedings of the 37th Conference of the International Group for the Psychology of Mathematics Education* (Vol. 4, pp. 425–432). PME

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Effectiveness of Problem-Centered Learning in Enhancing Senior High School Students' Achievements in Genetics

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ABSTRACT

Twenty-first-century competencies and mathematical literacy have many overlapping features. Although mathematical literacy is one of the necessary components to create 21st-century skills, each individual needs to understand mathematical literacy to solve the problems encountered in daily life. This study examined the effects of pre-service teachers' mathematical literacy self-efficacy on their perceptions of 21st-century skills efficiency. A total of 230 pre-service primary school teachers, 102 (44.3%) male and 128 (55.7%) female, participated in this study. The Mathematical Literacy Self-Efficacy scale and 21st Century Skills Efficiency Perceptions scale were used as data collection tools. Quantitative data were analyzed with structural equation modeling. The following measures were employed: Mathematical literacy self-efficacy positively affects perceptions of learning and innovation skills, mathematical literacy self-efficacy positively affects perceptions of life and career skills, and mathematical literacy self-efficacy affects perceptions of information-media and technology skills positively. The finding suggested that a significant and strong relationship was found between pre-service primary school teachers' mathematical literacy efficacy and 21st century skills efficiency and its sub-categories.

Keywords: mathematical literacy, 21st-century skills, structural equation modeling, pre-service teachers.

Introduction

Today's education doctrine considers transferable skills very important and is rapidly evolving to meet global education needs (Kotsiou et al., 2022). Furthermore, education seeks to equip students with the skills necessary to face an unpredictable future (Meegan et al., 2022). It is argued that education's main roles are to contribute to both the business sector and society, empowering students to develop their abilities, meet their social obligations, and maintain social cultures and values (Trilling & Fadel, 2009). In addition to these roles, education is a concept that is affected by the development of an individual and also has a direct impact on society.

One of the core objectives of modern education is integrating 21st-century skills—creativity, critical thinking, collaboration, and communication—into curricula (Jumriani & Prasetyo, 2022). These skills are crucial for personal and professional success and sustaining societal advancement in the digital era (Bybee, 2010). The need for these skills is increasingly recognized, especially given the global challenges in economic growth, competitiveness, and social cohesion (Voogt & Pareja Roblin, 2012). Thus, educational systems worldwide emphasize cultivating these abilities to prepare learners for complex, interdisciplinary problem-solving and adapting to the rapid technological changes that define the 21st century.

In this context, self-efficacy emerges as a pivotal construct that connects the teaching and learning of 21st-century skills with educational outcomes, particularly in areas like mathematics, where these skills are essential for deeper cognitive engagement (Pajares, 1996). According to Bandura (1994), self-efficacy is "people's beliefs about their capabilities to produce designated levels of performance that exercise influence over events that affect their lives" (p.1). Martin and others (2019) also explained self-efficacy as individuals' personal beliefs about planning and performing their own actions. Teachers' self-efficacy refers to teachers' beliefs in their capacity to carry out the educational process effectively and successfully. Self-efficacy beliefs affect individuals' emotions, thoughts, motivations, and actions. In mathematics education, for instance, a strong sense of self-efficacy can enhance motivation, effort, and persistence, which are crucial for mastering complex skills (Zimmerman, 2000).

As education moves towards a competency-based model that emphasizes lifelong learning and adaptability, understanding the link between self-efficacy and 21st-century skills becomes essential. Research indicates that students with higher self-efficacy beliefs in subjects like mathematics tend to engage more actively and demonstrate resilience in the face of challenges (Bandura, 1997; Schunk & Pajares, 2005). Integrating self-efficacy within the framework of 21st-century education goals enriches educational research and supports the broader mission of preparing students for personal success and societal contribution.

21st Century Skills

21st-century skills aim to provide students with the learning and application skills necessary for the development of today's globalized society (Rajoo et al., 2022). The implementation of 21st-century skills and competency-based learning demonstrates positive action in global education systems to develop a wider range of skills beyond traditional literacy and simple numeracy skills. There is broad agreement and important common interests in national and international qualification frameworks on the importance of 21st-century skills (UNESCO, 2021). This consensus is supported by the necessary educational situations to equip learners with usable knowledge and skills, rather than teaching outdated basic-level skills.

At this point, there are three basic skills that have become the focus of 21st-century learning: "information, media, and technology skills", "learning and innovation skills," and "life and career skills" (Alismail & McGuire, 2015). One of the sub-themes of these focal skills is "critical thinking and problem solving" (Saavedra & Opfer, 2015). Mathematics comes to the forefront as a course in which critical thinking and problem-solving skills are taught, and these skills should be taught to children from an early age. In addition, critical thinking includes the activities or skills of filtering, analyzing, criticizing, and summarizing information according to one's expertise (Güner & Gökçe, 2021). Teachers are expected to have these skills, and teachers with 21st-century competence will be able to apply these skills to their lesson practices.

Many organizations have emphasized the skills required for the 21st century. Partnership for 21st Century Learning ([P21], 2002) stated these competencies as critical thinking, applying knowledge to new situations, analyzing knowledge, grasping new ideas, communicating, collaborating, problem solving, and decision making. OECD (2019) stated these competencies as communication, mathematization, representation, reasoning and discussion, developing strategies to solve problems, using symbolic, formal, and technical language and operations, and using mathematical tools. The International Society for Technology in Education (ISTE) emphasized that students should have skills such as communication and collaboration, creativity and innovation, critical thinking, research and knowledge fluency, digital citizenship, problem-solving, and decision making. In other words, although there are different definitions of the skills that students should have in the 21st century, it generally focuses on how students can realize what they can do with the knowledge they have acquired, and how they will use what they have learned in a real context. In addition, when the competencies stated by organizations such as P21 and OECD for the 21st century are examined, the competencies covered by mathematical literacy are at the core of 21st-century skills.

Globally, there is a growing emphasis on teaching competencies related to 21st-century skills (Reimers, 2021). The abilities and attitudes of teachers are crucial to the successful application of 21st-century education in the classroom (Shafiee & Ghani, 2022); however, the process of 21st-century skills into the classroom practice is unfortunately not at the desired level. One of the biggest reasons for this is that teachers do not feel sufficiently competent in this regard. The slow pace is partly attributed to the complexity of the integration process, which involves content, pedagogy, and assessment alignment (Volman et al., 2020). Teachers with a high level of self-efficacy could handle any difficulties in the classroom and improve the quality of instruction (Bandura, 1977). Considering these, teachers are the prominent leaders for implementing 21st-century pedagogy into practice, there is a need to focus more on teacher self-efficacy (Schleicher, 2012).

Mathematical Literacy Self-Efficacy

One of the fundamental skills that everyone should possess is 21st-century literacy competence, another mathematical literacy self-efficacy (Umbara & Suryadi, 2019). OECD (2019) defines mathematical literacy as the formulation, use, and interpretation of mathematics by individuals. Mathematical literacy is the ability of individuals to understand and apply some mathematical practices such as principles, operations, and problem solving in daily life (Ojose, 2011). In other words, mathematical literacy involves mathematical reasoning and the application of mathematical concepts, procedures, facts, and tools for mathematical prediction. Another definition of mathematical literacy is that it helps to understand the role of mathematics in the world, to draw informed conclusions, and to make the decisions that people need as creative, active, and informed citizens (Hrynevych et al., 2022). Mathematical literacy has several core competencies (Rizki & Priatna, 2019) such as mathematical thinking and reasoning, mathematical argumentation, mathematical communication, modeling, problem posing and solving, representation, and technology use.

Modern primary school mathematics courses also provide students with content that improves their problem-solving and critical thinking skills and creative activities (Mirzaxolmatovna et al., 2022). In this context, critical thinking and problem-solving skills have an important place in daily life and in the field of mathematics. In addition, being able to think critically and solve problems can also be stated as understanding mathematics (Polya, 2017). Research shows that teachers who have developed mathematical literacy self-efficacy, who can solve problems and think critically, prevent the anxiety of teaching mathematics and the difficulties in answering students' mathematics questions (Doruk & Kaplan, 2016; Ural, 2015). In addition, students with high mathematical literacy self-efficacy also have high academic motivation and mathematics achievement (Gan & Peng, 2024). Geng and others (2023) suggest that individuals with different mathematical literacy self-efficacy levels may have different learning times and learning styles.

The accuracy of primary school students in acquiring 21st-century mathematical skills between different groups of students (for example, low- and high-performing students) is of interest because these may require a different focus in interventions (Oudman et al., 2022). Mathematics teaching styles are essential in increasing students' achievement in life and school, and their mathematical self-efficacy. Especially in recent years, while mathematics skills lead the learning stages of the 21st century, classroom teachers also use 21st-century learning skills to develop better mathematical learning environments for their students (Rajoo et al., 2022).

A prospective teacher must possess mathematical literacy skills to effectively formulate, apply, and interpret mathematics in various contexts, including the ability to perform mathematical reasoning and utilize concepts (Sawatzki & Sullivan, 2018). Considering the difficulty of prospective teachers who still need to become competent in giving confidence to their students and carrying out the teaching process in an ideal way, prospective teachers must have high mathematical literacy self-efficacy perceptions. It is also essential to investigate self-efficacy perceptions, which may provide important clues for mathematics (Topbaş Tat, 2018). Analyzing the self-efficacy perceptions of prospective teachers during their education, determining their competencies, and taking measures in line with the results is one of the critical steps in preparing them for their professions. Investigating self-efficacy perceptions is essential, as it may provide important clues for mathematics (Özgen & Bindak, 2008).

Mathematical Literacy Self-Efficacy and 21st Century Skills

Mathematical literacy self-efficacy is one of the necessary components for building 21st-century skills efficacy. In this context, interest in the effect of mathematical literacy self-efficacy on 21st-century skills is increasing. By strengthening their self-efficacy, teachers can more effectively apply teaching strategies such as problem-based learning and inquiry-based learning, which are compatible with the development of 21st-century skills (Öpengin & Elmas, 2023). However, integrating these skills into mathematics and other subjects is progressing slowly (Varas et al., 2023), and there are not many studies determining the effect of pre-service teachers' mathematical literacy self-efficacy on their 21st-century skills (Yenilmez & Ata, 2019). Determining the impact of mathematical literacy self-efficacy on prospective teachers, who will educate their students in the future on their 21st-century skills, is an essential factor in realizing effective teaching strategies and practices. In this context, it is important to determine the effects of pre-service teachers' mathematical literacy self-efficacy on their 21st-century skills.

Twenty-first-century self-efficacy and mathematical literacy have many overlapping features (Niemi et al., 2018). Although mathematical literacy is one of the necessary components to create 21st-century skills (Julie et al., 2017), each individual needs to understand mathematical literacy to solve the problems encountered in daily life (Rizki & Priatna, 2019). Students who develop mathematical literacy and 21st-century skills cope more easily with the competitive global changes they need to prepare themselves after graduating from the relevant schools (Haviz & Maris, 2020). In conclusion, the mathematically literate skills of individuals (e.g., problem-solving, reasoning, argument generation, and communication) overlap with the 21st-century skills stated by P21 (2019). In other words, as stated by Julie et al. (2017), mathematical literacy is the basis of 21st-century skills. However, some studies have shown that self-efficacy can directly affect mathematical learning (e.g., academic engagement and achievement) without relying on mathematical literacy alone (Geng et al., 2023; Li et al., 2020). In this study, the aim was to examine the relationship between pre-service teachers' perceptions of 21st-century skills self-efficacy and their mathematical literacy self-efficacy.

Teachers' self-efficacy beliefs significantly influence their teaching practices and students' learning outcomes. Research suggests that teachers with lower self-efficacy may feel less confident in delivering complex tasks that require 21st-century skills, potentially avoiding or simplifying such tasks to minimize cognitive load for themselves and their students (Bandura, 1997; Klassen & Tze, 2014). This reduction in task complexity not only limits opportunities for students to engage deeply with content but also hampers the development of essential competencies (Tschannen-Moran & Hoy, 2001). Conversely, teachers with high self-efficacy are more likely to adopt innovative teaching strategies and encourage critical thinking, problem-solving, and creativity among their students, which are fundamental components of 21st-century skills (Kahraman & Demirtaş, 2021).

As pre-service teachers develop their instructional practices, understanding the relationship between their mathematical literacy self-efficacy and 21st-century skill efficacy is essential. Teachers who feel capable of mathematical literacy are more likely to implement tasks that demand higher-order thinking, fostering a classroom environment that supports students' development in line with the broader educational goals of preparing learners for complex societal and professional challenges (Darling-Hammond, 2010). This study, therefore, aims to examine the relationship between pre-service teachers' perceptions of 21st-century skills efficacy and their mathematical literacy self-efficacy, highlighting the crucial role of self-efficacy in preparing learners for the challenges of the future.

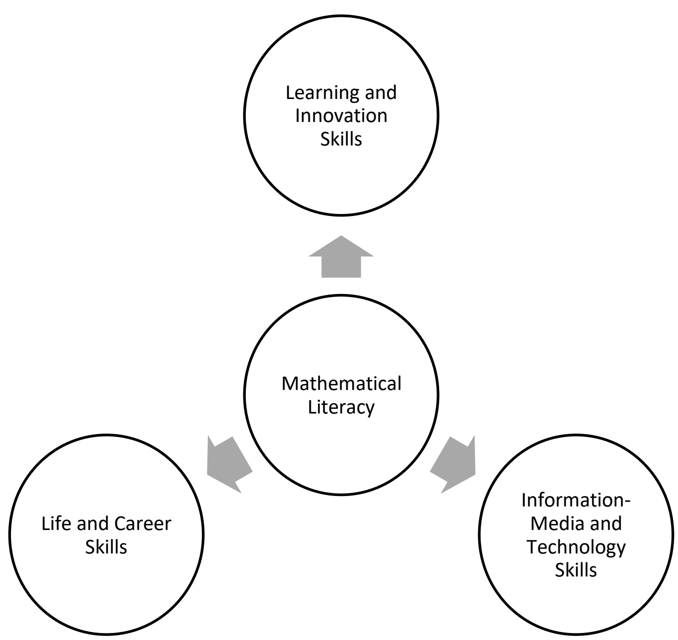
Empirical research highlights a significant relationship between teachers' self-efficacy beliefs and their ability to integrate 21st-century skills into classroom practice effectively. For example, Göçen et al. (2023) emphasized that high teacher self-efficacy positively influences the integration of complex educational competencies, thereby enhancing student engagement and learning outcomes. However, recent studies (Yılmaz & Turan, 2020) have indicated that the specific impact of mathematical literacy self-efficacy on pre-service teachers' proficiency in delivering 21st-century skills remains underexplored. Addressing this gap, this study examines how mathematical literacy self-efficacy correlates with perceived efficacy in 21st-century skills among pre-service teachers, thereby contributing to existing research by clarifying this critical interrelationship (Niemi et al., 2018).

Objectives of the Study

The hypotheses of this study were determined according to the model indicated in Figure 1.

Figure 1.

Structural Equation Modeling



Ha1: Mathematical literacy self-efficacy positively affects perceptions of learning and innovation skills.
Ha2: Mathematical literacy self-efficacy positively affects perceptions of life and career skills.
Ha3: Mathematical literacy self-efficacy positively affects perceptions of information-media and technology skills.

Method

Participants

The research group was formed through the convenience sampling method. The convenience sampling method is known as a practical sampling method because it provides convenience to researchers in terms of time and cost (Yıldırım & Şimşek, 2018). The participants in the study were selected among the pre-service primary school teachers attending the Institute of Educational Sciences at Eskisehir Osmangazi University in Eskisehir, Türkiye. In addition, the participant pre-service primary school teachers were studying at the same faculty of the state university in the city center. A total of 230 pre-service primary school teachers, 102 (44.3%) male, and 128 (55.7%) female, participated in the study. In addition, 76 (33%) of the pre-service teachers in the study are 1st year students, 55 (23.9%) 2nd year students, 56 (24.3%) 3rd year students, and 43 (18.7%) 4th year students.

Data Collection Tools

In this study, the Mathematical Literacy Self-Efficacy scale and the 21st Century Skills Efficiency Perceptions scale were used as data collection tools. Information on these scales is given.

Mathematical Literacy Self-Efficacy Scale

The related scale was developed by Özgen and Bindak (2008) to determine pre-service teachers' self-efficacy for mathematical literacy. The aim of this scale is to determine pre-service teachers' attitudes towards mathematical literacy self-efficacy beliefs (Özgen & Bindak, 2008). The scale consists of one dimension and 25 items. The items in the scale were structured in a five-point Likert-type scale as "totally agree, agree, undecided, disagree, and strongly disagree". Twenty-one of the items in the scale contain positive judgments, and four of them contain negative judgments. While scoring the statements containing negative judgments, the scores were reversed for calculation. While the Cronbach alpha internal consistency coefficient of the related scale was 0.924, it was calculated as 0.912 in this study. This finding shows that the scale is reliable. Confirmatory factor analysis (CFA) was applied to the data set to gather evidence for the construct validity of the scale. As a result of the analysis, it was calculated as $\chi 2/df=0.94$, *CFI*=0.99, *AGFI*=0.93, *NNFI*=0.99, *RMSEA*=0.010, *SRMR*=0.094. The relevant values confirm that the scale is compatible with the data set (Kline, 2019).

21st Century Skills Efficiency Perceptions Scale

The related scale was developed by Anagün et al. (2016) to determine pre-service teachers' perceptions of 21st-century skills. The aim of this scale is to determine to what extent pre-service teachers have 21st-century skills (Anagün et al., 2016). There are three sub-dimensions and a total of 42 items on the scale. The statements in the scale are in a five-point Likert model as "never, rarely, sometimes, often, and always". There are 18 items in the Learning and Renewal Skills sub-dimension, 16 items in the Life and Career Skills sub-dimension, and eight items in the Information-Media and Technology Skills sub-dimension. The Cronbach alpha internal consistency coefficient of the whole scale was calculated as 0.889, the Learning and Renewal Skills sub-dimension 0.845, the Life and Career Skills sub-dimension 0.826, and the Information-Media and Technology Skills sub-dimension

0.810. In this study, the Cronbach alpha internal consistency coefficient of the whole scale was 0.925, the Learning and Renewal Skills sub-dimension was 0.905, the Life and Career Skills sub-dimension was 0.812, and the Information-Media and Technology Skills sub-dimension was 0.829. Available data indicate that the scale is reliable. CFA was applied to test the construct validity of the scale. As a result of the analysis, it was found as $\chi 2/df=0.53$, *CFI*=0.99, *AGFI*=0.92, *NNFI*=0.99, *RMSEA*=0.010, *SRMR*=0.091. Existing values indicate that the scale is in good agreement with the data (Kline, 2019).

Analysis of Data

Research data were analyzed using SPSS and the R programming language. While SPSS was used for descriptive analysis, the Lavaan package in the R programming language (Yves, 2012) was used for structural equation modeling. Before the data was analyzed, the suitability of the data for the analysis was checked. In this context, assumptions such as missing data, extreme value, sample size, normality, linearity, and multicollinearity were examined.

According to Tabachnick and Fidell (2013), missing data should be checked before starting the analysis. In this context, first of all, it was checked whether there was missing data in the data set, and it was determined that there was no missing data in the data set. Then, univariate and multivariate outlier control were performed on the data set. To determine univariate outliers, the raw scores in the data set were converted into Z scores, and the scores outside the -3 to +3 score range were accepted as univariate outliers. As a result of the relevant analysis, the information of a total of nine participants who were outside the range of scores determined were excluded from the data set. Then, the Mahalanobis values of the data were examined to determine the multivariate outliers in the data set. Tabachnick and Fidell (2013) state that 0.001 is the critical value for the Mahalanobis value, and values below this value are considered as multivariate extreme values. After the tests were carried out in this context, the data of three participants with a Mahalanobis value below 0.001 were deleted.

After univariate and multivariate outliers were removed from the data set, the sample size of the study was 218. According to Heck and Thomas (2015), a sample size of at least 200 people is sufficient for structural equation modeling. The sample size is expected to be sufficient for structural equation modeling.

For structural equation modeling, the univariate and multivariate normality conditions of the data set should be determined. For the univariate normality assumption, the kurtosis and skewness values were examined, and the relevant values were found to be between -2 and +2. According to George and Mallery (2010), the values of kurtosis and skewness in the range of -2 to +2 indicate that the data provide univariate normality. According to Field (2009), univariate normality is a prerequisite for multivariate normality, but ensuring univariate normality does not guarantee multivariate normality. Therefore, the Henze-Zirkler multivariate normality test was applied to the data set to determine whether the data set provides multivariate normality. The relevant value was calculated as 2.03, and it was determined that the data set did not meet the multivariate normality assumption ($p>0.01$). The Unweighted Least Squares (ULS) method was preferred as the estimation method in the multivariate analysis process. Because Koğar and Yılmaz Koğar (2015) revealed that ULS produces more effective results than other methods in cases where the assumption of multivariate normality cannot be met.

The multicollinearity problem is expressed as the high similarity between independent variables. According to Tabachnick and Fidell (2013), correlation, VIF, and tolerance values between independent variables should be examined. A correlation between independent variables greater than 0.85, a VIF value greater than 10, and a tolerance value less than 0.01 are indicators of multicollinearity (Kline, 2005). First of all, the correlation between independent variables was examined. Relevant values were found to be between 0.468 and 0.595. Afterward, it was determined that the VIF values were between 1.404 and 1.695, and the tolerance values were between 0.590 and .0712. As a result, there is no multicollinearity problem among the independent variables. After it was determined that the data set met the assumptions required for feed analysis, descriptive analyses were applied to the data set. The values obtained after the related analyses are presented in Table 1.

Table 1

Descriptive Statistics of Mathematical Literacy Self-Efficacy and 21st Century Skills Efficacy Perceptions Scales and Sub-Dimensions

Scales and Sub-Dimensions	N	Min	Max	$\bar{x}$	SD
Mathematical Literacy Self-Efficacy Scale	218	2.20	4.76	3.56	0.43
21st Century Skills Competence Perceptions Scale	218	3.00	5.00	4.00	0.35
Learning and Renewal Skills Sub-Dimension	218	2.33	5.00	3.74	0.46
Life and Career Skills Sub-Dimension	218	3.00	5.00	4.19	0.35
Information-Media and Technology Skills Sub-Dimension	218	3.00	5.00	4.21	0.47

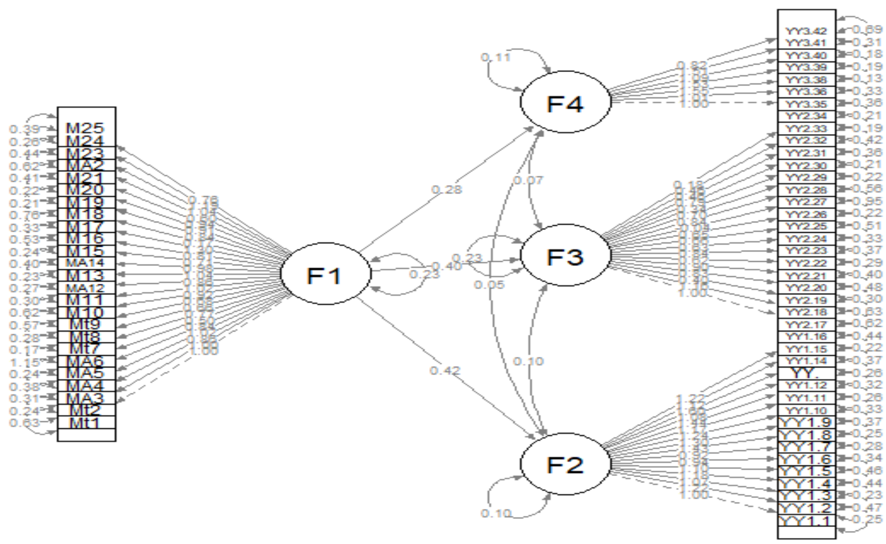
Table 1 shows that the mean score of mathematical literacy self-efficacy is $\bar{x}$=3.56. On the other hand, the mean score of the mathematical literacy self-efficacy of the participants in the research is above average. In addition, the mean score of 21st-century skills efficacy is high ($\bar{x}$=4.00). The perceptions of 21st-century skills efficiency of the participants are at a high level. Moreover, when the mean scores of the sub-dimensions of the 21st Century Skills Efficacy were examined, it was determined that only the perceptions of learning and renewal skills were relatively lower ($\bar{x}$=3.74), and the other sub-dimensions were at a higher level ($\bar{x}$=4.19, $\bar{x}$=4.21). The participants have lower perceptions of learning and renewal skills compared to their perceptions of life and career, information-media, and technology skills. As a result, the mean scores of both the mathematical literacy self-efficacy and 21st-century skills perception scales are high.

Results

Path analysis was applied to reveal the effect of mathematical literacy on learning and renewal, life and career, and information-media technologies skills. The results are presented in Figure 2. In Figure 2, F1 represents mathematical literacy self-efficacy, F2 refers to learning and renewal skills, F3 refers to life and career skills, and F4 refers to information-media and technology skills. Figure 2 shows that learning and renewal skills of mathematical literacy (.42, t=9.92, p<.05), life and career skills (.40, t=9.81, p<0.5), and information-media and technology skills (.28, t=7.33, p<.05) were found to be significant and positive predictors. In other words, the Ha1, Ha2, and Ha3 hypotheses examined within the scope of the research were supported. Furthermore, when the levels of significant effects are examined, it can be stated that a one-unit increase in mathematical literacy self-efficacy causes a 0.42 increase in learning and renewal skills, a 0.40 increase in life and career skills, and a 0.28 increase in information-media and technology skills. In other words, it can be stated that mathematical literacy self-efficacy has a similar level of effect on learning and renewal skills and life and career skills, while it has less effect on information-media and technology skills.

Figure 2.

Path Analysis Diagram for the Tested Model



Confirmatory factor analysis revealed the model's compatibility with the data. Table 2 presents indicators related to the aforementioned analysis.

Table 2

Fit Indices of the Tested Model

Fit Index	Good Fit	Acceptable	Value Achieved	Conclusion
RMSEA	0 ≤ RMSEA ≤ 0.05	.05 <RMSEA ≤ .08	.01	Good Fit
SRMR	0 ≤ SRMR ≤ .05	.05 <SRMR ≤ .10	.09	Acceptable
TLI	.95 ≤ NNFI ≤ 1.00	.90 ≤ TLI <.95	.99	Good Fit
CFI	.95 ≤ CFI ≤ 1.00	.90 ≤ CFI <.95	.99	Good Fit

Source: Schermelleh-Engel et al., 2003

Table 2 shows that the RMSEA, TLI, and CFI values, which are among the fit indices of the established model, are at a good level, and the SRMR value is between acceptable values. Briefly, there is a good level of compatibility between the model established and the data.

Discussion and Conclusion

This study examined the effect of mathematical literacy self-efficacy on learning and renewal, life and career, and information-media technology skills. Pre-service primary school teachers' mathematical literacy self-efficacy was found to positively affect the perceptions of learning and renewal, life and career, and information-media technology skills, and all hypotheses were supported. For the first hypothesis, the effect of mathematical literacy self-efficacy on learning and renewal skills was examined, and the hypothesis was supported. As stated by Julie and others (2017), mathematical literacy is required to form the basis of 21st-century skills. In this study, it was concluded that pre-service teachers' mathematical literacy self-efficacy affects their 21st-century skills efficiency. Within the scope of learning and innovation skills specified by P21, creativity and innovation, critical thinking and problem solving, communication and cooperation skills come to the fore. Individuals of the 21st century are expected to develop original ideas to find solutions to problems they face in daily life, find different solutions from different perspectives, look critically at problems, adapt quickly to new situations, and take responsibility by collaborating (Karatas & Zeybek, 2020). In this context, it has been concluded that prospective primary school teachers who are mathematically literate will also have these skills.

For the second hypothesis, the effect of mathematical literacy self-efficacy on life and career skills was examined, and the hypothesis was supported. Within the scope of P21's Life and Career Skills, flexibility and adaptability, initiative and self-direction, social and intercultural skills, productivity and accountability, and leadership and responsibility skills were prerequisites. It is also concluded that mathematical literacy positively affects the skills within the scope of life and career, as stated by P21. For the third hypothesis, the effect of mathematical literacy self-efficacy on information-media technologies skills was examined, and the hypothesis was supported. Information literacy, media literacy, and ICT (information, communication, and technology) literacy are included within information-media technologies skills. In this context, mathematical literacy self-efficacy was found to positively affect information literacy, media literacy, and ICT literacy. Also, digital literacy, which is an important basic skill that individuals should have, especially in the 21st century, is higher among mathematically literate individuals. In other words, individuals with strong mathematical literacy self-efficacy are generally more comfortable with technology and more likely to adapt to new digital tools. As Novita and Herman (2021) stated, it is challenging to develop individuals' digital literacy, and information literacy, media literacy, and ICT literacy can be improved by improving the individual's mathematical literacy.

Mathematical literacy self-efficacy is an important determinant of an individual's ability to develop 21st-century skills. However, pre-service teachers possessed a limited and incomplete understanding of the concept of mathematical literacy (Yenilmez & Ata, 2013). By developing mathematical literacy self-efficacy, individuals can also develop skills such as critical thinking, leadership, problem solving, digital literacy, collaboration, and communication skills necessary for success in the 21st century. The mathematical literacy self-efficacy of prospective teachers is important for preparing the future generations. Students are first introduced to mathematics in formal education through primary-school teachers, and therefore, the importance of mathematics literacy of prospective primary school teachers should not be ignored (Tarım et al, 2017). In the tested model, a significant and strong relationship was found between mathematical literacy self-efficacy and 21st-century skills. Developing 21st-century skills also requires the development of mathematical literacy self-efficacy.

By demonstrating the positive impact of mathematical literacy self-efficacy on perceptions of 21st-century skills efficiency, this study makes an important contribution to the research examining the relationship between these two concepts. While previous studies have primarily addressed mathematical literacy in the context of academic achievement or problem-solving skills (e.g., Pelitli & Yetim, 2020; Zehir & Zehir, 2016), this study adds a new perspective to the literature by showing how it shapes pre-service teachers' perceptions of 21st-century skills. The findings emphasize that strategies to strengthen mathematical literacy self-efficacy in teacher education programs are critical for developing 21st-century skills efficiency. In this context, it is suggested that teacher education curricula should include modules that provide mathematical literacy practice through real-life problems and support self-efficacy.

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References

Alismail, H. A., & Mcguire, P. (2015). 21st-century standards and curriculum: Current research and practice. *Journal of Education and Practice*, *6(*6), 150-154. https://www.doi.og/10.1177/004723951771076.

Anagün, Ş. S., Atalay, N., Kılıç, Z., & Yaşar, S. (2016). Öğretmen adaylarına yönelik 21. yüzyıl becerileri yeterlilik algıları ölçeğinin geliştirilmesi: geçerlik ve güvenirlik çalışması [The development of a 21st century skills and competences scale directed at teaching candidates: Validity and reliability study. *Pamukkale University Journal of Education, 2016*(40), 160–175. https://doi.org/10.9779/puje768

Bandura, A. (1977). Self-efficacy: Toward a unifying theory of behavioral change. *Psychological Review, 84*(2), 191-215.https://doi.org/10.1037/0033295x.84.2.191

Bandura, A. (1994). Self-efficacy. In V. S. Ramachaudran (Ed.), *Encyclopedia of human behavior* (Vol. 4, pp. 71-81).Academic Press.

Bandura, A. (1997). *Self-efficacy: The exercise of control.* W. H. Freeman.

Bybee, R. W. (2010). Advancing STEM education: A 2020 vision. *Technology and Engineering Teacher, 70*(1), 30–35.

Darling-Hammond, L. (2010). *The flat world and education: How America's commitment to equity will determine our future.* Teachers College Press.

Doruk, M., & Kaplan, A. (2016). Sınıf ve ilköğretim matematik öğretmeni adaylarının matematik kaygılarının incelenmesi. *Kastamonu Eğitim Dergisi*, *21*(4), 1505-1522.

Field, A. (2009). *Discovery statistics using SPSS.* (3rd ed.). Sage.

Gan, Y., & Peng, J. (2024). Effects of teacher support on math engagement among Chinese college students: A mediated moderation model of math self-efficacy and intrinsic value. *Children and Youth Services Review*, *156*, 107369. https://doi.org/10.1016/j.childyouth.2023.107369

Geng, Y. B., Ying, B., Wang, X., Lin, J., Zhang, M. Y., & Liu, Y. L. (2023). The relationship between parent–child communication and English academic engagement among middle school students: A moderated mediation model. *European Journal of Psychology of Education*, *38*(4), 1-18. https://doi.org/10.1007/s10212-023-00676-7

George, D., & Mallery, M. (2010). *SPSS for Windows Step by Step: A Simple Guide and Reference*. Boston.

Göçen, G., Demirtas Tolaman, T., & Azizoglu, N. I. (2023). Using technology to support creative writing: How it affects teachers' digital writing skills and their gains from digital technology. *International Journal of Psychology and Educational Studies*, *10*(2), 422-440. https://doi.org/10.52380/ijpes.2023.10.2.1039

Güner, P., & Gökçe, S. (2021). Linking critical thinking disposition, cognitive flexibility and achievement: Math anxiety's mediating role. *Journal of Educational Research, 114*(5), 458-473. https://doi.org/10.1080/00220671.2021.1975618

Haviz, M., & Maris, IM. (2020). Measuring mathematics and science teachers' perceptions on thinking and acting in 21st-century learning. *Journal for the Education of Gifted Young Scientists, 8*(4), 1319-1328. http://dx.doi.org/10.17478/jegys.747395.

Heck, R. H., & Thomas, S. L. (2015). *An introduction to multilevel modeling techniques*. (3rd edition). Routledge.

Hrynevych, L. M., Khoruzha, L. L., Rudenko, N. M., & Proshkin, V. V. (2022). STEM education in the context of improving the science and mathematics literacy of pupils. *Journal of Physics: Conference Series, 2288*(1), 012031. https://doi.org/10.1088/1742-6596/2288/1/012031

Julie, H., Sanjaya, F., & Anggoro, A.Y. (2017, August). The students' ability in the mathematical literacy for uncertainty problems on the PISA adaptation test. In *AIP Conference Proceedings* (Vol. 1868, No. 1, p. 050026). AIP Publishing LLC.

Jumriani, J., & Prasetyo, Z. K. (2022). Important roles of local potency based science learning to support the 21st century learning. *European Journal of Formal Sciences and Engineering*, *5* (1), 38-51.

Kahraman, S., & Demirtaş, Z. (2021). The effect of teacher self-efficacy on teaching practices for developing 21st-century skills. *Journal of Educational Studies*, 35(2), 129-145. https://doi.org/10.1177/073112142199221

Karatas, K., & Zeybek, G. (2020). The Role of the academic field in the relationship between self-directed learning and 21st century skills. *Bulletin of Education and Research*, *42*(2), 33-52. https://files.eric.ed.gov/fulltext/EJ1281054.pdf

Klassen, R. M., & Tze, V. M. C. (2014). Teachers' self-efficacy, personality, and teaching effectiveness: A meta-analysis. *Educational Research Review*, 12, 59–76. https://doi.org/10.1016/j.edurev.2014.06.001

Kline, R. B. (2019). *Principles and practice of structural equation modeling.* (4th Edition). Guilford Publications, Inc.

Kline, R. B. (2005). *Principles and practice of structural equation modeling.* (2nd University Edition). Guilford Publications, Inc.

Kotsiou, A., Fajardo-Tovar, D. D., Cowhitt, T., Major, L. & Wegerif, R. (2022). A scoping review of future skills frameworks. *Irish Educational Studies*, *41*(1), 171–186.

Li, L., Liu, Y. T., Peng, Z. F., Liao, M. Q., Lu, L. C., Liao, H., & Li, H. (2020). Peer relationships, motivation, self-efficacy, and science literacy in ethnic minority adolescents in China: A moderated mediation model. *Children and Youth Services Review*, 119, 1–8. https://doi.org/10.1016/j.childyouth.2020.105524

Martin, L. E., Mulvihill, T. M., Schunk, D., Ginsberg, A., Guskey, T., Kohl, K., Ladson-Billings, G., Meier, D., Peace, T., Popham, J., Slavin, R., Sleter, C., & Tirri, K. (2019). Voices in education: Teacher self-efficacy in education. *Teacher Educator*, *54*(3), 195-205. https://doi.org/10.1080/08878730.2019.1615030

Meegan, J., Casey, E., & O'Brien, N. (2022). *Integrating 21st-century skills into Irish primary schools: A pilot study on the outcomes, experiences and observations of teachers prepared.* Hibernia College Report No 1. https://iasc.hiberniacollege.com/handle/20.500.13012/135

Mirzaxolmatovna, X. Z., Ibrokhimovich, F. J., & Ne'matovna, R. S. (2022). Methodology of teaching mathematics in primary education. *Journal of Pedagogical Inventions and Practices, 7,* 81-83.

Niemi, H., Shuanghong, N. I. U., Vivitsou, M., & Baoping, L. I. (2018). Digital storytelling for twenty-first-century competencies with math literacy and student engagement in China and Finland. *Contemporary Educational Technology*, *9* (4), 331-353.

Novita, R., & Herman, T. (2021, February). Digital technology in learning mathematical literacy, can it be helpful?. *Journal of Physics: Conference Series, 1776*(1), 012027.

OECD. (2019). *PISA 2018 assessment and analytical framework.* PISA, OECD Publishing.

Ojose, B. (2011). Mathematics literacy: Are we able to put the mathematics we learn into everyday use. *Journal of Mathematics Education, 4*(1), 89-100.

Oudman, S., van de Pol, J., & van Gog, T. (2022). Effects of self-scoring their math problem solutions on primary school students' monitoring and regulation. *Metacognition and Learning, 17*(1), 213-239.

Öpengin, E. & Elmas, İ. (2023). The examination of the relationship between prospective teachers' creative self-efficacy and teaching 21st century skills. *Anadolu University Journal of Education Faculty, 7*(4), 804-818.

Özgen, K., & Bindak, R. (2008). Matematik Okuryazarlığı Öz-Yeterlik Ölçeğinin Geliştirilmesi [The development of self-efficacy scale for mathematics literacy]. *Kastamonu Education Journal, 16*(2), 517–528.

P21. (2019). *Framework for 21st century learning definitions*. Partnership for 21st Century Learning. https://www.battelleforkids.org/networks/p21/frameworks-resources

Pajares, F. (1996). Self-efficacy beliefs in academic settings. *Review of Educational Research*, 66(4), 543-578. https://doi.org/10.3102/00346543066004543

Partnership for 21st Century Skills (2002). *Learning for the 21st Century A Report and Mile Guide for 21st Century Skills*. Partnership for 21st Century Skills.

Pelitli, E. N., & Yetim, H. (2020). Sınıf öğretmeni adaylarının matematik dersine yönelik matematik okuryazarlık öz-yeterliliği. *ASEAD*, *7*(8), 163–180. https://dergipark.org.tr/tr/download/article-file/1222199

Polya, G. (2017). *A new look at how to solve mathematical method* (Translation Editor: Burak Selçuk Soyer) (Translation from 1st Edition). Tubitak Popular Science Books, Ankara.

Rajoo, M., Balasubramaniam, G., Auliah, A., Shaharudin, S., & Efendi, R. (2022). The role of Malaysian mathematics teachers in promoting 21st Century learning. *Journal of Positive School Psychology,* 1310-1318. http://mail.journalppw.com/index.php/jpsp/article/view/3242/2106

Reimers, F. M. (2021). In search of a twenty-first century education renaissance after a global pandemic. in Reimers, F. (Ed.), *Implementing deeper learning and 21st century education reforms: Building an education renaissance after a global pandemic* (1-37), Springer. https://doi.org/10.1007/978-3-030-57039-2

Rizki, L. M., & Priatna, N. (2019, February). Mathematical literacy as the 21st century skill. *Journal of Physics: Conference Series, 1157*(4), 042088.

Saavedra, A. E. & Opfer, V. D. (2015). *Learning 21st century skills requires 21st century teaching*. Bobst Library.

Sawatzki, C., & Sullivan, P. (2018). Shopping for shoes: Teaching students to apply and interpret mathematics in the real world. *International Journal of Science and Mathematics Education, 16*, 1355-1373.
Schermelleh-Engel, K., Moosbrugger, H., & Müller, H. (2003). Evaluating the fit of structural equation models: Tests of significance and descriptive goodness-of-fit measures. *Methods of Psychological Research Online*, 8, 23–74.
Schleicher, A. (2012). *Preparing teachers and developing school leaders for the 21st century: Lessons from around the world.* OECD Publishing.
Schunk, D. H., & Pajares, F. (2005). Competence perceptions and academic functioning. In A. J. Elliot & C. S. Dweck (Eds.), *Handbook of competence and motivation* (pp. 85-104). Guilford Press.
Shafiee, N. S., & Ghani, M. A. (2022). The influence of teacher efficacy on 21st century pedagogy. *International Journal of Learning, Teaching and Educational Research, 21*(1), 217-230. https://doi.org/10.26803/ijlter.21.1.13
Tabachnick, B. G., & Fidell, L. S. (2013). *Using multivariate statistics* (6th ed.). Allyn and Bacon.
Topbaş Tat, E. (2018). Matematik Öğretmen Adaylarının Matematik Okuryazarlığı Öz-Yeterlik Algıları. *İlkogretim Online*, *17*(2). https://doi.org/7710.17051/ilkonline.2018.418887
Tschannen-Moran, M., & Hoy, A. W. (2001). Teacher efficacy: Capturing an elusive construct. *Teaching and Teacher Education*, 17(7), 783-805. https://doi.org/10.1016/S0742-051X(01)00036-1
Trilling, B. & Fadel, C. (2009). *21st Century Skills: Learning For Life in Our Times.* Jossey-Bass.
Umbara, U., & Suryadi, D. (2019). Re-interpretation of mathematical literacy based on the teacher's perspective. *International Journal of Instruction, 12*(4), 789–806. https://doi.org/10.29333/iji.2019.12450a
United Nations Educational, Scientific and Cultural Organization (UNESCO) (2021). *Futures literacy: an essential competency for the 21st century.* Author. https://en.unesco.org/futuresliteracy/about (Accessed: 14 September 2022).
Ural, A. (2015). Matematik öz-yeterlik algısının matematik öğretmeye yönelik kaygıya etkisi. *Kuramsal Eğitimbilim Dergisi*, *8*(2), 173-184. https://www.ocerints.org/intcess14_epublication/papers/459.pdf
Varas, D., Santana, M., Nussbaum, M., Claro, S., & Imbarack, P. (2023). Teachers' strategies and challenges in teaching 21st century skills: Little common understanding. *Thinking Skills and Creativity*, *48*, 101289. https://doi.org/10.1016/j.tsc.2023.101289
Volman, M., Karssen, M., Emmelot, Y., & Heemskerk, I. (2020). The focus of schools on twenty-first–century competencies and students' experience of these competencies. *The Curriculum Journal*, *31*(4), 648-665.
Voogt, J., & Pareja Roblin, N. (2012). A comparative analysis of international frameworks for 21st century competences: Implications for national curriculum policies. *Journal of Curriculum Studies*, 44(3), 299-321. https://doi.org/10.1080/00220272.2012.668938
Yenilmez, K., & Ata, A. (2019). Effects of mathematical literacy course on pre-service mathematics teachers' self-efficacy levels of mathematical literacy. *The Journal of Academic Social Science Studies*, *6*(2), 1803-1816. http://dx.doi.org/10.9761/jasss_675
Yıldırım, A. & Şimşek, H. (2018). *Qualitative research methods in social sciences* (11th Edition). Ankara: Seçkin Publishing.
Yılmaz, D., & Turan, H. (2020). Self-efficacy beliefs of pre-service teachers in teaching first reading and writing and mathematics. *Participatory Educational Research*, *7*(1), 257-270. https://doi.org/10.17275/per.20.15.7.1
Yves, R. (2012). Lavaan: An R package for structural equation modeling. *Journal of Statistical Software, 48*(2), 1-36. https://doi.org/10.18637/jss.v048.i02

Zehir, K. & Zehir, H. (2016). Investigation of elementary mathematics student teachers' mathematics literacy self-efficacy beliefs according to some variables. *International Journal of Education, Science and Technology, 2*(2), 104-117. https://arastirmax.com/en/system/files/dergiler/243888/makaleler/2/2/arastirmax-ilkogretim-matematik-ogretmen-adaylarinin-matematik-okuryazarligi-oz-yeterlik-inanc-duzeylerinin-cesitli-degiskenler-acisindan-incelenmesi.pdf

Zimmerman, B. J. (2000). Self-efficacy: An essential motive to learn. *Contemporary Educational Psychology*, 25(1), 82–91. https://doi.org/10.1006/ceps.1999.1016

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What Should STEM Education Look Like?: A Book Review of "Frameworks for Integrated Project-Based Instruction in STEM Disciplines"

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BOOK INFORMATION

Title: *Frameworks for Integrated Project-Based Instruction in STEM Disciplines*
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Introduction

> Students who experience only traditional instruction are taught to follow someone else's procedures without necessarily understanding them; to do repetitive, simple tasks with no larger purpose behind them; to work individually; and to obey authority. Project-Based Instruction, conversely, can prepare students to confront complex tasks through collaboration, productive struggle, inventiveness, creative problem-solving, and constructive cycles of feedback and revision (Petrosino et al., 2024, p. 157).

In their 2024 book *Frameworks for Integrated Project-Based Instruction in STEM Disciplines*, Anthony J. Petrosino, Candace Walkington, and Denise Ekberg paint a full picture of project-based instruction, referred to as PBI throughout the book. The authors note this method can also be named project-based learning, which many readers may be more familiar with. As they describe it, PBI is a tool that can address a wide variety of learning and social goals for students within STEM classrooms. While this book is relevant for most PreK-12 educators interested in PBI as an instructional approach within their classroom, it reads more toward an audience of curriculum developers and teacher educators. The authors offer a clear picture of what elements are necessary for quality PBI in STEM, but also include some history and context for PBI. The book also provides some suggestions for how to move forward with PBI, from the classroom to school districts and beyond.

As a former project-based campus leader and PBI teacher-trainer and a current pre-service teacher educator, much of this book affirmed my own experiences, though there were certainly historical and contextual implications new to me. Below, I provide a brief summary of this volume and then offer insights and connections I found most valuable for today's educational landscape.

Overview of the Book

The first chapter provides an overarching definition of PBI and then delineates how PBI compares to six other educational approaches (e.g., problem-based learning and case-based learning). From there, chapter two moves into a historical overview of the project method – an educational movement beginning in the 1920s United States that arose in opposition to education serving solely as a tool to provide students with "the basics." The project method emphasized "a philosophy in which learning facts that could be used later in life was secondary to learning as a part of life" (Petrosino et al., 2024, p. 17). At the center of the project method is the idea that students direct the learning to develop deep content knowledge, problem-solving skills, and the ability to transfer knowledge across various applications.

After exploring the history of the project method and its connections to PBI, chapter three explores six core components of what the authors refer to as "big P Projects" – projects that are classified as PBI. These are in contrast to "little p projects," which PBLWorks (n.d.) refers to as "dessert." Little p projects are designed to showcase learning after instruction, instead of driving learning throughout instruction. The authors then also briefly discuss the 5-E lesson model and its potential for daily lesson structure within a PBI unit. However, the authors nod to other models (e.g., the STAR Legacy cycle) that could also function well for day-to-day learning within a Project. Chapter four then provides teachers and curriculum developers with practical steps and suggestions for developing a Project plan.

Chapter five moves into what PBI could look like in three fields of STEM education – engineering, computer science, and mathematics. In engineering, PBI is related to the "maker" movement and the recent trend of "makerspaces." In computer science, the authors discuss how PBI could allow for interdisciplinary computer science applications, as well as challenging and rewarding problems for students to tackle. Finally, in mathematics, the authors relate PBI to other ideas in math education, including Jo Boaler's work on math education reform (e.g., *Experiencing School Mathematics (2002)*, *What's math got to do with it? (2015)*, and *Mathematical Mindsets (2016)*).

Chapter six addresses what it really looks like to implement PBI on a wide scale. The authors begin with one of my favorite lines in the entire book about the dangers of making PBI widespread: "A challenge is the danger of popularity, including the pendulum swing of reform initiatives and an expansion of dubious or shallow implementations" (Petrosino et al., 2024, p. 133). When scaling PBI, the core elements can easily be lost, no matter how well-intentioned the educators are. To address these concerns, the authors discuss an approach to training administrators, which includes providing information on the history of PBI and a demo for administrators to experience this method firsthand. Finally, the authors discuss assessment methods within Projects and the potential for the future of PBI within various STEM fields, as well as opportunities for technology integration within PBI.

What is STEM education for?

Having utilized and taught PBI (and similar approaches) for over a decade, reading this book resonated with my experiences and knowledge of the method. More specifically, I want to highlight some points of the book I found to be most impactful when it comes to education today and, potentially, an answer to the question "What is STEM education for?"[1]

The book provides one possible answer to this question in how PBI in STEM education can allow for the inclusion of equity and justice issues. In chapter five, when discussing potential inroads for PBI in various STEM fields, the authors incorporate profiles of a few specific instructors. One

[1] I borrowed this question from Dr. Paulette Evans (personal communication, February 21, 2025) in a recent training I attended about teaching the same undergraduate PBI ed prep course mentioned at a few points throughout this book.

instructor discussed how PBI has serious implications for the sociopolitical engagement of his students. The book even provides a list of goals for "Proposed Equity and Justice Projects for PreK-12 Science Education" (Petrosino et al., 2024, p. 127). These goals and the vignette also connect to a later section entitled "PBI and Issues of Equity, Diversity, and Access" (p. 157). While these brief sections are just one possible reason or opportunity for PBI, a greater discussion of these issues could offer a highly compelling answer to what STEM education is for.

The authors also elaborate on how PBI might offer a method for students to learn by serving their own communities. This "service learning" approach has strong possibilities to fulfill the principles of experiential learning that John Dewey (1938) set out, as the authors indicate. It also connects to the work of Nel Noddings (1992) and her emphasis on the need for centering care in education. As another answer to the question "What is STEM education for," I have seen that service learning, designed around students caring about each other and their community, has great success in building lasting knowledge and students' capacities to care for each other and the world around them.

PBI v Cookie-Cutter Curricula

I have taught in secondary math classrooms, both traditional and project/problem-based, for over 10 years. I have seen both the detriments of a test-based educational culture and the benefits of a more de-standardized project-based approach. So, whereas the nods of this book in the direction of "What is STEM education for?" were noteworthy to me, by far the most interesting portion of this book was a four-and-a-half-page section entitled "Challenges to PBI From Systems Steeped in the Modernist Tradition."

This section compares the needs of PBI in STEM with the checklist-driven reality of our current educational system, with its highly structured lesson plans, curricula, and standards. The book does not outright reject the streamlining of curricula to a "series of steps" (Petrosino et al., 2024, p. 139). It does, however, offer up a way in which the organic nature of PBI, being driven by community needs and student passions, can be incorporated into our educational system in a way that allows students to master STEM concepts while seeing themselves as powerful and passionate actors in their own education. In this way, PBI offers up an alternative to what Freire (1970/2000) termed the banking concept of education, where "knowledge is a gift bestowed by those who consider themselves knowledgeable upon those whom they consider to know nothing" (p. 72).

Overall Impressions

Frameworks for Integrated Project-Based Instruction in STEM Disciplines is a practical guide to PBI in STEM. This volume is informative, with depth on the history, methods, and applications of PBI, and it provides context for how PBI can be implemented in STEM classrooms with considerations for modern-day implementation. Though since the depth and context do seem to be more aimed at curriculum developers and teacher educators at the graduate and post-graduate level, I could imagine an educator in the field would also benefit from an accompanying workbook with practical approaches to implementing the stages of planning described in chapter four. No matter your role in education, though, the picture of PBI painted by Petrosino et al. (2024) is an optimistic one - "Our challenges may be great, but helping each other learn and grow can help us transcend the issues we face now and prepare us as we forge ahead into the future" (p. 161).

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References

Boaler, J. (2002). *Experiencing school mathematics: Traditional and reform approaches to teaching and their impact on school learning*. Erlbaum.

Boaler, J. (2015). *What's math got to do with it? How parents and teachers can help children learn to love their least favorite subject* (2nd ed.). Penguin.

Boaler, J. (2016). *Mathematical mindsets: Unleashing students' potential through creative math, inspiring messages & innovative teaching*. Wiley.

Dewey, J. (1938). *Experience and education*. Macmillan.

Evans, P. (2025, February 21). *Project based instruction* [Virtual training session]. UTeach STEM Educators Association.

Freire, P. (1970/2000). *Pedagogy of the oppressed* (M. B. Ramos, Trans.; 30th anniversary ed.). Continuum.

Noddings, N. (1992). *The challenge to care in schools: An alternative approach to education*. Teachers College Press.

PBLWorks. (n.d.). *"Doing a Project" vs. Project-Based Learning.* PBL Works. https://www.pblworks.org/doing-project-vs-project-based-learning

Petrosino, A. J., Walkington, C., & Ekberg, D. (2024). *Frameworks for integrated project-based instruction in STEM disciplines*. Information Age Publishing, Inc.