Exploration of Critical Thinking Attributes in an Innovative Undergraduate STEM Program

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Abstract

Experiences during post-secondary education can accentuate the ongoing, ever-changing process of developing 21st-century skills for undergraduate students. These 21st-century skills, including critical thinking (CT), are important for students to develop for competitive job placement after graduation. The future workforce requires diverse knowledge, skills, and dispositions to navigate complex and ever-changing jobs, especially in science, technology, engineering, and mathematics (STEM) fields. This project aimed to qualitatively investigate previously determined quantitative attributes of CT to gain a deeper understanding of how these attributes manifest themselves in undergraduate STEM scholars' problem-solving and decision-making. Twelve program undergraduate student participants from a STEM professional development program partook in completing materials for this study. We used a phenomenology approach to explore the nuances of CT attributes from the responses of our program participants. We explored how the eight CT attributes (induction, analysis, inference, evaluation, deduction, interpretation, explanation, numeracy) emerged from participant responses, in isolation and in interaction with each other in undergraduate STEM students' responses to real-world scenarios to find potential trends or insights to better understand the intricate nature of critical thinking as a construct. While we aimed to explore CT attributes in isolation based on their previously defined definitions, our findings demonstrate that certain CT attributes occurred concurrently with other CT attributes at higher frequencies than others (e.g., analysis and induction). These concurrent attributes show that undergraduate students identified various entry points to a real-life scenario, and simultaneously found multiple solutions to these complex problems. The findings of this exploratory study suggest areas for STEM program improvement based on the qualitative examination of whether CT attributes are present, and how they might also happen concurrently more frequently when undergraduate students face real-life decision-making scenarios. Findings from this study will help create a more robust program model for undergraduate student development to meet STEM workforce demands and competitive job placement after graduation. A deep understanding of what makes up this complex construct is essential to increase students' CT skills. Further research in this area may explore how CT attributes offer additional insights for framing undergraduate professional development programs. With careful attention to distinct and concurrent attributes, carefully designed professional development might be more effective and transferrable to STEM fields.

Keywords: STEM, critical thinking, undergraduates, program, qualitative

Introduction

Recruiting, preparing, and supporting a robust 21st-century workforce in these complex and evolving times is a high priority for the public and private sectors in the United States. Along with technical skills, the future workforce requires diverse knowledge, skills, and dispositions to navigate jobs, especially in science, technology, engineering, and mathematics (STEM) fields. Researchers and practitioners point to a lack of 21st-century skills (e.g., critical thinking, problem-solving, communication, collaboration) as a major factor impacting undergraduate students' access to and continuation in the growing field of STEM (e.g., Goodman et al., 2015; Noonan, 2017). Similarly, undergraduate students are described as being under-prepared to manage the complex professional conditions they face after graduating college (Kegan & Lahey, 2009; Pascarella et al., 2011).

Many stakeholders are looking to postsecondary institutions to be key players in addressing these current and future workforce concerns. Studies have revealed undergraduate engagement in educational practices can support and increase student development (e.g., Barber et al., 2013). Integrating evidence-based educational practices through pre-professional training programs are proven strategies that foster student development (e.g., Bonner et al., 2019; Cutucache et al., 2016; Gordon, 2017; Kuh, 2008; Sommers et al., 2021; Snodgrass Rangel et al., 2021; Nelson et al., 2018; Nelson & Cutucache, 2017; Quitadamo et al., 2008). Factors of undergraduate student development include their content competence, their ability to showcase learning to others (performance), and recognition of their competence and ability in areas by others (e.g., Carlone & Johnson, 2007; Herrera et al., 2012). These factors are often influenced by interacting with others and are aligned with an individual's various social and cultural identities (Herrera et al., 2012). For example, in STEM fields, it has been shown that experiential learning opportunities such as college professional development experiences support the growth of critical thinking and executive functioning of undergraduate students (e.g., Bonner et al., 2019; Snodgrass Rangel et al., 2021).

The development of critical thinking and executive functioning in STEM is important, as undergraduate students are expected to apply these skills to complete their degrees and as they matriculate into the workforce (National Academy of Sciences [NAS], 2010; Stelter et al., 2020; Xu, 2016; Xue & Larson, 2015). Critical thinking is a highly complex construct with many iterations and measurements proposed over time (Weschler et al., 2018). Broadly stated, critical thinking is achieving one's goals to evaluate the most efficient pathway to success (Wechsler et al., 2018). According to the American Philosophical Association's 'Delphi report' (Facione, 1990a), the multidimensional nature of critical thinking is influenced by and composed of a variety of processes, including dispositional, motivational, attitudinal, and metacognitive functions (Linn, 2000; Miele & Wigfield, 2014). This complexity makes developing, identifying, and measuring critical thinking a challenge.

Metacognitive functions include intentional, self-regulatory judgments as critical thinking attributes (e.g., analysis, induction, deduction, inference). On the other hand, effective dispositional thinking is presented in individuals' ability to be open-minded and flexible in their evaluation as they consider their personal biases, gather relevant information, and consider the reasonableness of their criteria and evaluation. For example, Butler (2012) found that there was a significant, direct relationship between individuals who scored higher on critical thinking assessment tools and those who reported less adverse outcomes in their personal lives. Attending undergraduate students' personal circumstances and attitudes about learning can increase overall critical thinking. Previous research has also shown that critical thinking attainment is not as closely tied to age as it is to exposure to diverse educational experiences (Butler et al., 2012; Franco et al., 2017). Therefore, it is crucial to develop strategies that can support the critical thinking of students.

As the demand is high for a STEM workforce with strong critical thinking skills, examining how pre-professional STEM programs can complement broadly applicable skills, like critical thinking, with overall preparedness for competitive job placement with intentionally designed programming is vital. For undergraduates, engagement in professional development programs in college has been shown to support students' acquisition of valuable skills, such as critical thinking (e.g., Cutucache et al., 2016; Sommers et al., 2021; Nelson et al., 2017; Nelson & Cutucache, 2017). During this phase of early adulthood for traditional undergraduates, students concurrently develop their academic, professional, and personal identities (Baxter Magolda, 1999; Kegan, 1994; King & Kitchener, 1994; Mezirow, 2018; Perry, 1970). Thus, this time provides a crucial window of opportunity to identify educational practices that promote the advancement of highly demanding knowledge and skills (Barber et al., 2013). Employers expect STEM majors to exit their degree programs with practiced critical thinking skills such that the graduates are effective in the workforce. Therefore, quality pre-professional training is urgently needed to ensure that productive reality is exhibited in all STEM graduates (NAS, 2010; Stelter et al., 2020; Xu, 2016; Xue & Larson, 2015). Previous studies have identified that intentional demonstration and explanation around students' metacognition increases critical thinking in undergraduate students (Mulnix, 2012; Swanwick et al., 2014). The conception of critical thinking and practice within a particular discipline has practical implications for those interested in increasing students' critical thinking skills (Forbes, 2018). However, the nuances of critical thinking as a construct and variations of critical thinking attributes within different disciplines can make professional development challenging or ineffective. Overcoming these challenges to develop a STEM professional development approach that yields robust critical thinking capacity in trainees is our ultimate goal.

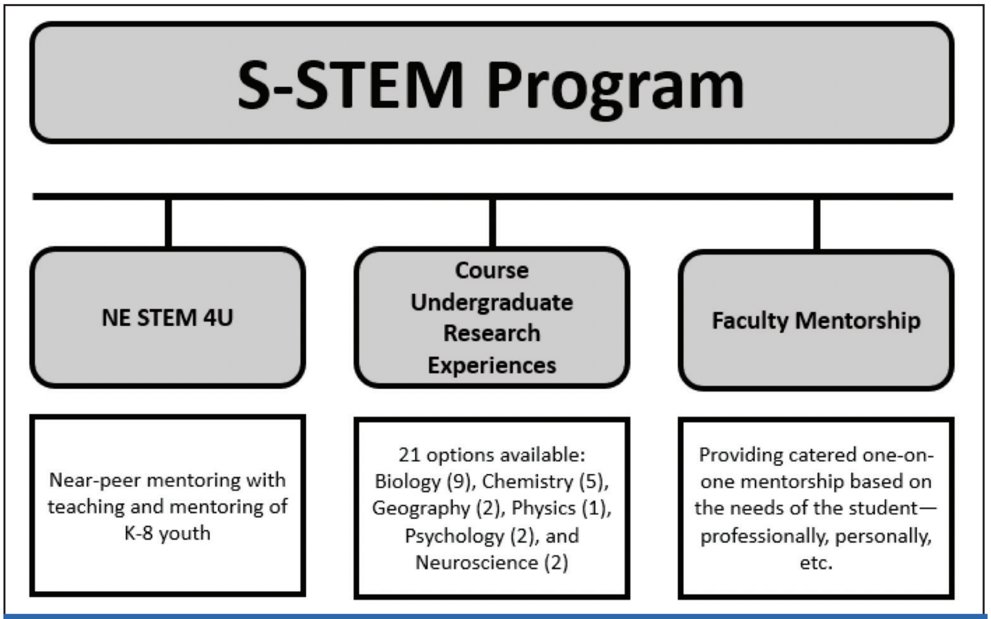


Figure 1. Components of the S-STEM program and how undergraduates in the program engaged in each component: Near-peer mentoring with teaching and mentoring of K-8 youth in the community via the Nebraska STEM For You (NE STEM 4U), participation in course-undergraduate research experiences (CUREs), and one-on-one faculty mentorship of undergraduates.

Project Setting

Since STEM-related fields are highly complex, diverse, and ever-changing, there is a need to support the development of undergraduate students beyond purely technical skills. These students also need to be trained in critical thinking for a successful launch into the 21st-century job sphere. This current study took place within an innovative, comprehensive undergraduate program called the National Science Foundation Scholarships in STEM (S-STEM) Track II project, EMPLOYEE: Empowering undergraduates via Mentorship, Professional development, Leadership, and Opportunities for Youth EngagEment (EMPLOYEE) program. The S-STEM program provides participants with financial scholarships and programmatic features designed to meet the needs of its participants, which include (i) mentorship of each undergrad student by university faculty members, (ii) participation in course-undergraduate research experiences (CUREs), and (iii) mentorship by the undergraduate student of local youth in the community (Nelson & Cutucache, 2017; Nelson et al., 2017; Leas et al., 2017; Cutucache et al., 2016; Stevenson et al., 2021). This three-pronged approach (summarized in Figure 1) aims to contribute to the national need for well-educated scientists, mathematicians, engineers, and technicians by supporting the retention and post-graduation success of low-income students with documented financial needs. We provide students in the program innovative professional development opportunities that prepare them for the 21st-century employment landscape, via the utilization of a locally developed mentoring and teaching program called Nebraska STEM For You (NE STEM 4U) program. The program provides pre-professional training to undergraduate students, while dually supporting the needs of local partners in the afterschool context in both urban and rural settings by providing youth in grades K-8 with hands-on, minds-on learning experiences around all areas of STEM (Stevenson et al., 2021; Cutucache et al., 2016). While supporting K-8 students, undergraduates also engage in near-peer mentoring by training new students in the program. Students in the S-STEM program are encouraged to have a CURE or other research experience embedded in their degree program and are individually paired with a university faculty mentor. All program components within the three-pronged approach are designed to develop students' STEM identity and critical thinking skills—the focus of this study.

Methodology

The goal of this project was to explore the nuances of critical thinking attributes as they are present or absent, in undergraduate STEM students engaged in a multi-dimensional programming model. We sought to understand how at the time the data were collected; the program engages participants in the innovative model of mentorship, course-based research experiences, and community-based teaching activities in STEM, and whether their engagement is meaningful in supporting their academic success and critical thinking skills. To do this, we recognized the importance of identifying and differentiating between and among the nuances of critical thinking as a construct. This process included exploring the contributing sub-factors of critical thinking, referred to as "attributes", as they manifest in participants' responses and interactions. With commercialized quantitative data in hand about our participants' scores on critical thinking as a whole and by attribute, we continued an additional phase of data collection and analysis to triangulate data using a mixed-methods design approach. This approach provided us with an opportunity to better understand not only the nuances of a multi-dimensional construct like critical thinking but also observe patterns or themes around the critical thinking attributes that might inform our program and other researchers and practitioners interested in undergraduate student development. The research questions of this study are: (1) To what extent are the eight critical thinking attributes present in undergraduate students' approaches to solving real-world scenarios? and (2) How are qualitative and quantitative analyses of critical thinking attributes similar or different within the S-STEM program of study?

Research Design

For this study, we used an explanatory, sequential mixed-methods approach (Creswell & Plano Clark, 2017; Tashakkori & Teddlie, 2003) where we were able to connect two different data collection phases with the quantitative phase being followed by the qualitative methodology of phenomenology. We aimed to explore the nuances of critical thinking attributes of recently recruited program participants measured at baseline into S-STEM program. We used descriptive statistics to examine the qualitative results. We implemented the qualitative approach phenomenology to describe the essence of the meaning of experiences as reported by participants (Teherani et al., 2015) through the Interpretative Phenomenological Analysis (IPA) approach by Smith et al., (2022). In this explanatory study, we attempted to describe how the critical thinking attributes surface and potentially interact, or not, in undergraduate STEM student participants' responses to relevant, real-world scenarios facing STEM students and early professionals. Rather than trying to elicit all critical thinking skills from the scenarios, our purpose with the open-ended prompts was to capture the perspectives of participants in our program when encountering complex problems and how they tackle them. We aimed to qualitatively explore and map out the critical thinking attributes of students with the already existing quantitative data, as both were explicitly linked by attribute definitions and could help triangulate data between the two phases.

Participants and Setting

The study took place at the University of Nebraska Omaha (UNO), a midwestern, large metropolitan university with an R2 (research-intensive) designation within a city with a population of over 500,000. Participants recruited for this program are STEM majors who have financial need and have demonstrated previous academic success (e.g., GPA). The study was approved by the UNO Institutional Review Board (IRB # 552-19-EP). We invited members of the S-STEM program to take part in the study via a survey. We explained to potential participants via writing that their involvement in the survey was voluntary and that they had the right to withdraw at any point during the survey, for any reason, and with no prejudice. During the data collection period of this study, there were 21 undergraduate student participants in the S-STEM program. Of these, 12 student participants in the program completed the survey for this study. Table 1 details the demographic information of the 12 student participants from the S-STEM program.

Description	Category	Number of Students (n)
Current Grade at Institution	*Freshman*	1
	Sophomore	4
	Junior	5
	Senior	2
Intended Major	*Biological Sciences*	5
	Engineering	2
	Computer Science	2
	Neuroscience	2
	Mathematics	1
	Environmental Science	1
Current GPA	*Range*	2.75 – 4.0
	Average	3.69
Disability	*Yes*	1
	No	9
	Do not wish to report	1
Gender	*Female*	8
	Male	3
	Do not wish to report	1
Ethnicity	*Non-Hispanic*	9
	Hispanic	1
	Do not wish to report	1
Race	*White*	8
	Black or African American	1
	Two or more races	2
	Do not wish to report	1
Provided NE STEM 4U Programming	*Yes*	12
	No	0
Participated in a CURE by Time of Data Collections	*Yes*	6
	No	6
Received Mentoring by Time of Data Collections	*Yes*	12
	No	0

Table 1. Participant demographic information.

Note: Because some participants are pursuing a dual-major pathway and some students opted out of responding to some questions, not all categories show 12 responses even though n=12. With initial baseline quantitative and demographic data in hand, we had many questions remaining about what we, as a program, could do to enhance the student's experience and critical thinking as STEM majors. This was only heightened in the context of the COVID-19 pandemic, which had changed the format of the three-pronged programmatic approach the year before, but now had all returned to in-person outreach, mentorship, and coursework. This led to ongoing qualitative data collection to establish a mixed-methodology approach to answer our research questions with the goal of program improvement in very challenging times.

Data Collection

For our quantitative data collection, participants completed a baseline assessment of their critical thinking skills via the California Critical Thinking Skills Test (CCTST) (Facione, 1990a; Insight Assessment, 2021) upon entry into the program. This is a widely used, validated, commercially available test (Facione, 1990b; Insight Assessment, 2021) that uses the consensus definition for critical thinking reached by experts (Facione, 1990a). The tool provides 40 engaging, scenario-based questions. The questions are drawn from a scientifically developed and tested item pool. We eliminated the timing obstacle and allowed students to take the test from any location, but requested they dedicate an hour without interruption. Participants only needed a stable internet connection, one uninterrupted hour, and a computer to complete the assessment. This quantitative assessment breaks down and defines each of the eight critical thinking attributes described in this study (induction, analysis, inference, evaluation, deduction, interpretation, explanation, and numeracy).

For our qualitative data collection, we invited participants to respond to a questionnaire in Fall 2021, distributed through Qualtrics, which gathered demographic information and participant responses to four critical thinking scenarios. Summaries of the four critical thinking scenarios are. Participants were: (i) asked to explain their approach to resolving an issue. (ii) prompted to reflect on methods of coming to an agreement. (iii) asked to imagine being pressured to acquiesce to someone else. (iv) prompted to consider an ethics issue. Appendix A contains the full text of all four critical thinking scenarios used in the study.

We collected demographic data via the questionnaire, however, all identifying information was removed before data analysis to protect the anonymity of participants. We provided participants with open-ended critical thinking prompts in the questionnaire to solve the presented problem. Critical thinking prompts were derived from previous research on critical thinking essays and scenarios (e.g., Ennis & Weir, 1985) and the four questionnaire prompts asked participants to consider different scenarios based on their experiences, current knowledge, and/or potential future decision-making actions. The prompts do not elicit any level of or prescriptive type of critical thinking but provide an opportunity for participants to explain their thinking process as they attend to real-life scenarios. The prompts provide situations for participants to evaluate pathways to success, hence, use their critical thinking (Wechsler et al., 2018). The open-ended questionnaire stated participants may or may not have experienced those scenarios in the past, but they were prompted to respond to the open-ended scenarios based on how they might approach the situation if given the opportunity. Participants had the freedom to complete the survey at their own pace and in their preferred location. Participants

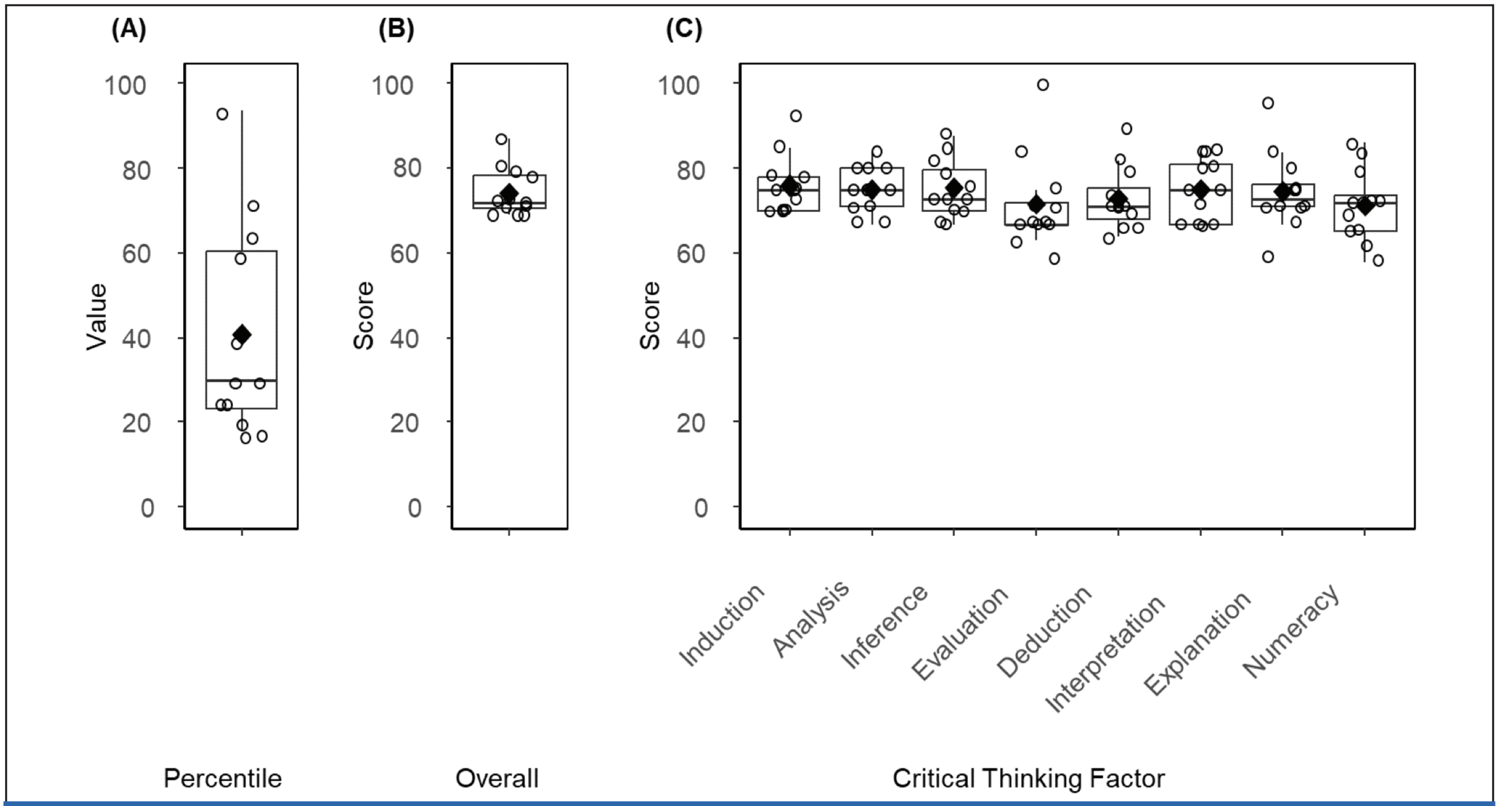


Figure 2. Boxplots show percentile (A) and raw scores for the overall score (B) and individual critical thinking factors (C) for 12 S-STEM students upon entry in our program at the California Critical Thinking Skills Test (CCTST). The lower border of the box shows the 25th percentile of the data, while the upper border of the box is the 75th percentile. Inside the box, black lines represent the median and diamonds indicate the mean. The length of the whiskers is defined as the 75th percentile plus 1.5 times the interquartile range and as the 25th percentile plus 1.5 times the interquartile range. Individual data points are shown as open circles.

were given the flexibility to complete the survey in one sitting or take a break and return to it later. There was no timeframe given to complete the survey.

Data Analysis

The quantitative data were analyzed using R version 4.2.2 (R Core Team, 2022) loaded with the package's car (Fox & Weisberg, 2019), Hmisc (Harrell, 2022), and corrplot (Wei & Simko, 2021). Shapiro-Wilk test and Levene's test (Whitlock & Schluter, 2015) were used to test the quantitative data for normal distribution and homogeneity of variances, respectively. As most of the quantitative data were not normal distributed, we used the Kruskal-Wallis test (Whitlock & Schluter, 2015) to test for differences in the medians of the critical thinking attributes and Spearman's rank correlations to test for correlations among the critical thinking attributes. Qualitative data analysis was an ongoing, recursive process of examining and interpreting the data among participants (Richards, 2005). Analysis of participants' responses to prompts followed the defined steps of IPA (Smith et al., 2022). The first author and second author completed the qualitative coding and analysis. Prior to the data analysis, the coders cleaned, de-identified, and evaluated participant responses. Coders then drafted a codebook (Appendix B) based on the CCTST's (Facione, 1990a) reasoning skills metrics (attributes) definitions found on the Insight Assessment website (Insight Assessment, 2021).

The initial round of coding focused on the eight critical thinking attributes. These attributes included induction, analysis, inference, evaluation, deduction, interpretation, explanation, and numeracy. The coding process included synthesizing and summarizing each attribute to find representative sample(s) for each attribute, where possible (see Appendix B). To ensure the reliability of results, we (the first and second authors) coded all participant responses simultaneously in MAXQDA qualitative analysis software, allowing us to resolve and reconcile any initial coding discrepancies in real-time. This coding procedure ensured the reliability and validity of coding by honoring the codebook definitions and clarifying the nuances of each attribute based on defined parameters. We integrated initial notes within the data by adding detailed comments as we simultaneously coded (Saldaña, 2016; Smith et al., 2022) to elaborate on any nuances in responses or additional themes that may be noteworthy for later analysis. MAXQDA2022 qualitative data analysis software housed all survey data, the codebook, and research memos documenting comments of particular interest during the analysis.

Results

Our quantitative baseline data showed that the 12 S-STEM students in our program performed on average at the 40.8th percentile at the California Critical Thinking Skills Test (CCTST) corresponding to a mean overall score of 74.2. The CCTST runs on a 100-point scale, with 50 being the lowest possible score. Within our data set, the students differed in their performance ranging from the 18th to the 94th percentile and scoring between 69 and 87, respectively (Figure 2A, B). The mean scores did not differ between the individual critical thinking attributes (Kruskal -Wallis, $\chi^2=7.566$, df=7, p=0.37; Figure 2C). The variation of the scores also did not differ between the critical thinking attributes (Levene's test, F(8,99)=0.522, p=0.837; Figure 2C).

Critical thinking attributes were correlated, although to a varying degree (Figure 3A). Explanation was the attribute with the most and strongest correlations with all other attributes. Numeracy, Evaluation, and Deduction also showed many correlations with other attributes, but they were fewer in numbers and generally less strong than the correlations of explanation. Interpretation and Analysis had the fewest correlations with other attributes. Interpretation was strongly correlated with Explanation, while Analysis correlated highly with Deduction and Numeracy. There seem to be two overlapping clusters of attributes that correlate with each other. One cluster includes Explanation, Evaluation, Induction, Interpretation, and Numeracy. The other cluster contains Analysis, Inference, Deduction, and Numeracy.

With these quantitative results and overlapping data points in hand, we decided to initiate a qualitative data

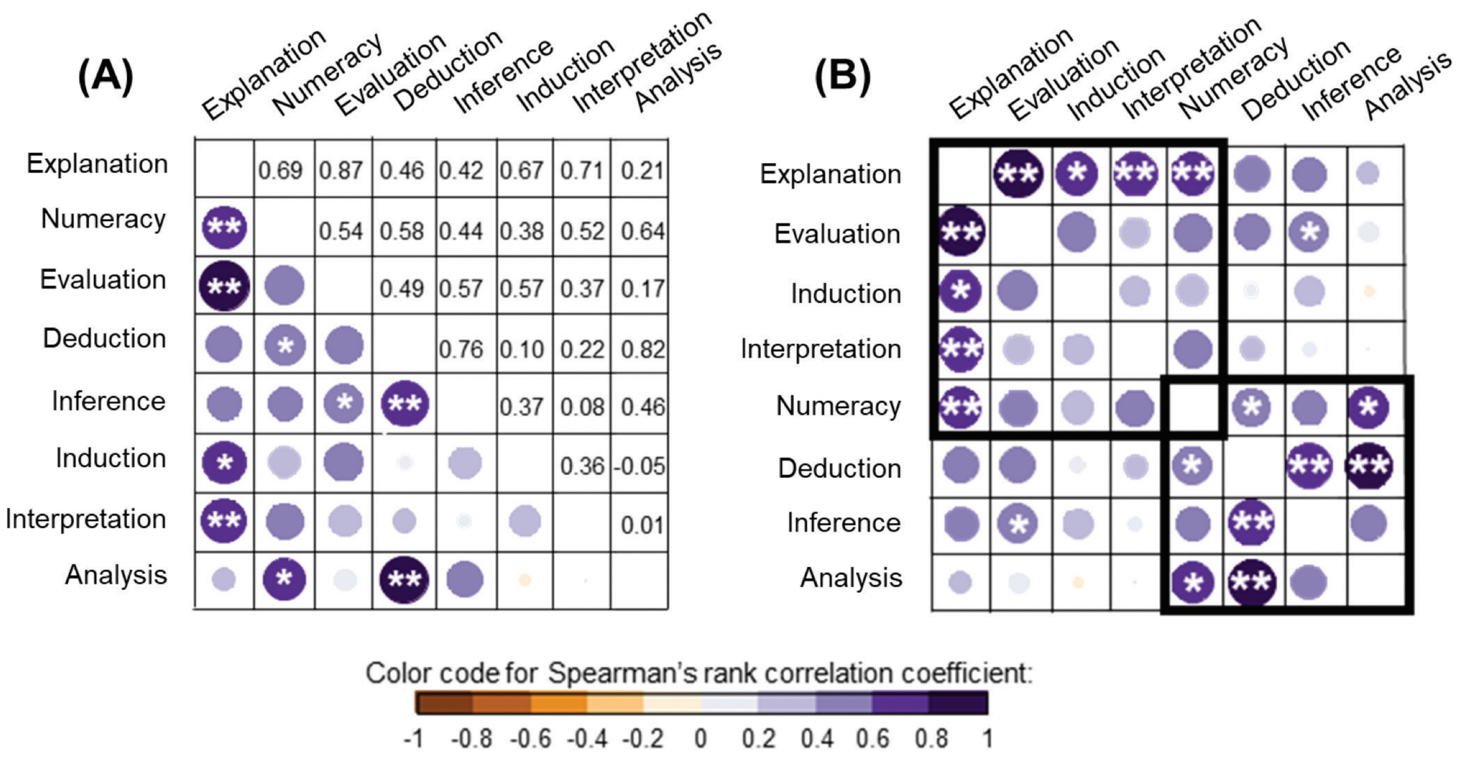


Figure 3. Correlations among critical thinking attributes are ordered either based on the number and strength of correlations of individual attributes with all other attributes (A) or grouped by attributes correlating strongly with each other (B). The numbers in the upper half of (A) are Spearman's rank correlation coefficients. The size and color of the circles in (A) and (B) correspond to the value of Spearman's rank correlation coefficients. One asterisk indicates a p-value of ≤0.05, while two asterisks represent a p-value of ≤0.01.

collection and analysis to identify these critical thinking attributes in students and how they might be present within participants' written responses to open-ended prompts. Because of the multidimensional nature of critical thinking incorporating individuals' dispositions, motivations, attitudes, and metacognitive functions (Facione, 1990a; Linn, 2000; Miele & Wigfield, 2014), a qualitative approach to support the existing quantitative baseline data was needed to inform ongoing program development. Qualitative data analysis allows researchers to examine "how people interpret...and attribute meaning to their experiences" (Merriam, 2009, p. 5) and answer questions beyond "what" and attend to the "how" and/or "why". Therefore, we aimed to explore the nuances of the eight critical thinking attributes to better understand to what extent and how they are present, or not, in participants' open-ended responses. Further, with integrated quantitative and qualitative data in hand, we sought to leverage a deeper understanding of critical thinking attributes to consider how programs, like this one, aimed at developing the overall critical thinking of undergraduate students, might be more intentional in designing and implementing professional development. We guided our study using the eight critical thinking skills descriptions provided by Facione (1990a) (Table 2).

Qualitatively, we investigated the occurrences and trends or patterns related to the critical thinking attributes in participant responses to real-world scenarios. Coded segments involved the identification of critical thinking skills in responses to prompts. The most exhibited critical thinking attributes by participants were Analysis and Induction, while Evaluation, Explanation, and Numeracy were attributes less prevalent or absent in the data (Figure 4).

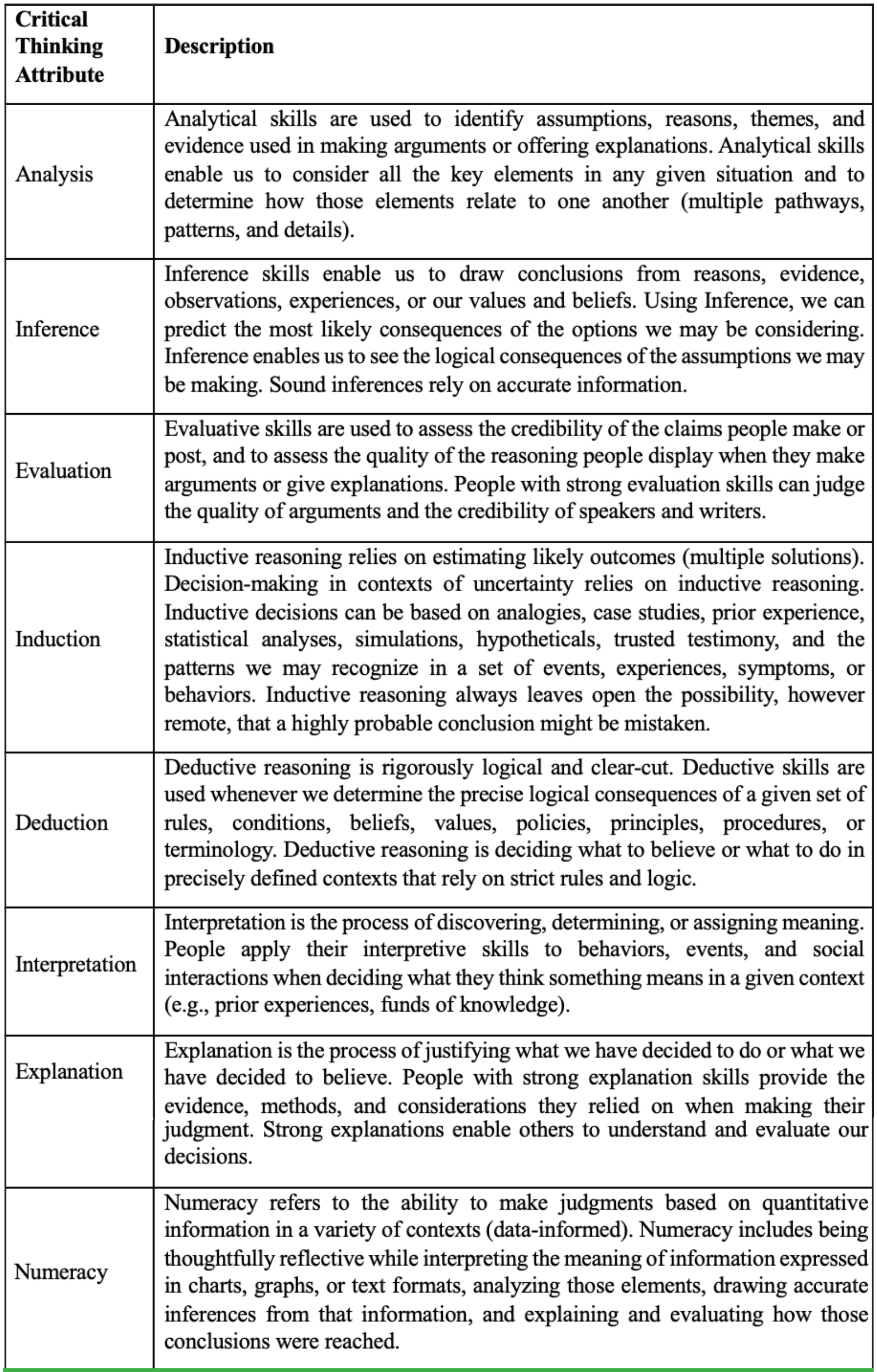
While pure saturation of attributes (those that occurred most often or not at all) was of interest to us in participant responses, we encountered that the most frequent occurrences of attributes also tended to occur in concurrence with another attribute in two ways. Also, two attributes were less prevalent or non-existent in our qualitative data findings. As we analyzed and integrated our quantitative findings with the additional layer of qualitative findings, we identified three themes in the data: (1) multiple steps and multiple pathways, (2) clarity of future direction, and (3) less prevalent or absent critical thinking attributes. We provide our analysis of the identified themes below.

Multiple Steps and Multiple Pathways

Within the qualitative data, the most frequent critical thinking attributes were Analysis and Induction (Figure 4). In terms of saturation, concurrences of Analysis and Induction attributes occurred in 8 out of 21 coded segments. In these cases, participants simultaneously considered multiple steps or considerations in approaching the scenario and multiple potential outcomes. An indicator of these occurrences was when participants included several if/then statements in the responses. Within these responses, participants also recognized that their decisions had implications on people outside of themselves (e.g., K-8 students, peers, the organization). For example,

> *I would handle this situation by admitting my mistake to the mentors I may be working with, as well as the students I'm mentoring, if appropriate. A scientific mistake that I made could be used as a good teaching lesson for the students in a sense of explaining any pertinent background information to further comprehension, followed by an explanation of my scientific mistake, what makes it wrong, and the correct methodology/answer to that scientific mistake. On the other hand, a misconception in my lesson plan would more than likely be rather boring and irrelevant to the students, so I'd probably address that issue with only the other mentor.*
>
> *Depending on if I'm already accepted into a graduate program or not, I would base my decision off that. If I am, I would perhaps not be able to stay but could offer to train someone who could help carry out the data collection. If I am not accepted into a program, I would stay and use it as an opportunity to grow as a researcher.*

Critical thinking often entails developing multiple solutions to ill-structured problems by assessing the outcomes



Critical Thinking Attribute	Description
Analysis	Analytical skills are used to identify assumptions, reasons, themes, and evidence used in making arguments or offering explanations. Analytical skills enable us to consider all the key elements in any given situation and to determine how those elements relate to one another (multiple pathways, patterns, and details).
Inference	Inference skills enable us to draw conclusions from reasons, evidence, observations, experiences, or our values and beliefs. Using Inference, we can predict the most likely consequences of the options we may be considering. Inference enables us to see the logical consequences of the assumptions we may be making. Sound inferences rely on accurate information.
Evaluation	Evaluative skills are used to assess the credibility of the claims people make or post, and to assess the quality of the reasoning people display when they make arguments or give explanations. People with strong evaluation skills can judge the quality of arguments and the credibility of speakers and writers.
Induction	Inductive reasoning relies on estimating likely outcomes (multiple solutions). Decision-making in contexts of uncertainty relies on inductive reasoning. Inductive decisions can be based on analogies, case studies, prior experience, statistical analyses, simulations, hypotheticals, trusted testimony, and the patterns we may recognize in a set of events, experiences, symptoms, or behaviors. Inductive reasoning always leaves open the possibility, however remote, that a highly probable conclusion might be mistaken.
Deduction	Deductive reasoning is rigorously logical and clear-cut. Deductive skills are used whenever we determine the precise logical consequences of a given set of rules, conditions, beliefs, values, policies, principles, procedures, or terminology. Deductive reasoning is deciding what to believe or what to do in precisely defined contexts that rely on strict rules and logic.
Interpretation	Interpretation is the process of discovering, determining, or assigning meaning. People apply their interpretive skills to behaviors, events, and social interactions when deciding what they think something means in a given context (e.g., prior experiences, funds of knowledge).
Explanation	Explanation is the process of justifying what we have decided to do or what we have decided to believe. People with strong explanation skills provide the evidence, methods, and considerations they relied on when making their judgment. Strong explanations enable others to understand and evaluate our decisions.
Numeracy	Numeracy refers to the ability to make judgments based on quantitative information in a variety of contexts (data-informed). Numeracy includes being thoughtfully reflective while interpreting the meaning of information expressed in charts, graphs, or text formats, analyzing those elements, drawing accurate inferences from that information, and explaining and evaluating how those conclusions were reached.

Table 2. Descriptions of the eight critical thinking skills

of potential solutions that required making judgments and guiding subsequent behaviors (King & Kitchener, 1994; Mezirow, 2018). Considering the personal impact of decisions on others highlights the complexity that can occur when Analysis and Induction occur simultaneously. Participants recognized the multiple courses of action needed to overcome obstacles. For example, participants resolved complications in their hypothetical mentoring experience by proposing to take alternative routes for problem-solving to positively impact their K-8 students and maintain relationships with peers. Within the data, participants leaned on prior experiences within and outside of the S-STEM program components to address these real-world scenarios. In addition, participants used available resources (e.g., peers, faculty members) to make more informed decisions. Similarly, participants weighed their options to make choices that best suited their academic and professional goals.

> *I would first try to fix the mistake, especially if it was regarding a topic that I knew a lot about. If it was unfixable, and the mistake ruined the entire lesson, then I would use the mentoring time to play a fun math game or trivia game.*

Within the data set, Analysis and Induction were the most saturated critical thinking attributes coded in the data and occurred frequently at the same time (concurrently). The concurrent occasions of Analysis and Induction represented how participants considered other stakeholders in their decision-making and the influence of their decisions on others. This facet of considering others may have led to why they recognized the many entry points to problem-solving (Analysis) and potential outcomes (Induction), elements routinely needed during S-STEM program teaching and mentoring of K-8 youth (Nelson et al., 2018).

As we considered our previous quantitative findings, Analysis and Induction were not significantly different from or between other critical thinking attributes. Further, Analysis was an attribute with the fewest correlations to other critical thinking attributes and there was no relationship, between Analysis and Induction, $r(12)= -.05$, $p>0.05$ (Figure 3). These two attributes were not connected within the same correlation cluster. Whereas the qualitative data presented unique concurrent occurrences of the two attributes, the quantitative data analysis provided seemingly minimal data to take action on as a program given our sample of participants. In conjunction, these analyses lead to more thinking around not only the qualitative prompts but also how these two data collection and analysis approaches might bring more light to the construct of critical thinking.

Clarity of Future Direction

The second most predominant concurrent coding of attributes occurred between Interpretation and Deduction. In this context, concurrent means that a given response included language that was coded as both Interpretation and Deduction. They were concurrently identified in 4 out of 21 coded segments. This combination of Interpretation and Deductive attributes revealed that immediate decision-making within closed parameters can still include long-term considerations of decision-making consequences. The occurrences of deductive thinking with the logical interpretation of actions for making decisions occurred when thinking about participants' future plans (e.g., graduate school, research experience). Interestingly, all four concurrent occurrences of Interpretation and Deduction in the findings were in response to the following prompt:

> *Your advisor wants you to stay in their lab one extra year to collect data on an important project. You are set to graduate at the end of the semester after meeting all of your program requirements. Your advisor wants you to collect the data for their lab, which might also add to your professional credentials, but*

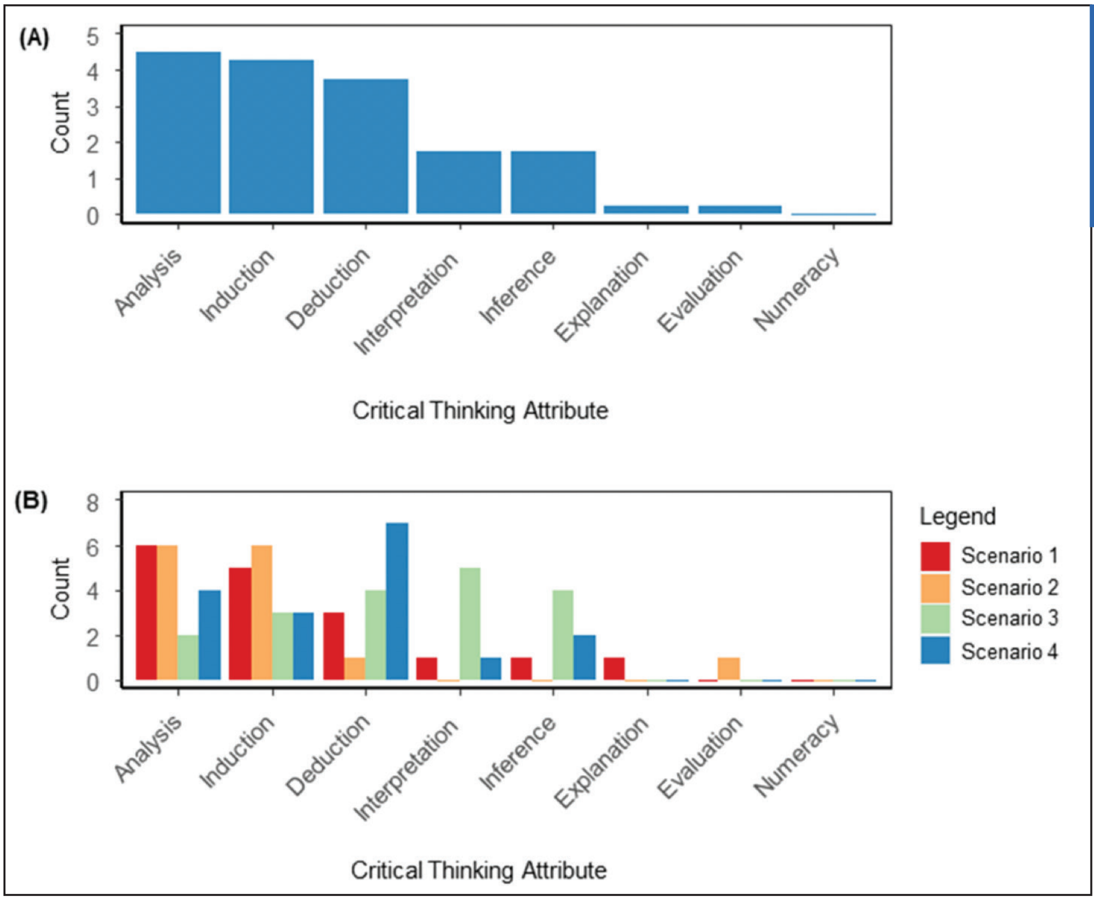


Figure 4. Critical thinking skills exhibited by the 12 students in our sample in four critical thinking-eliciting scenarios. (A) shows the mean use of critical thinking attributes, while (B) displays the use of critical thinking attributes for each scenario.

Note: Numeracy was not identified in any of the four critical thinking-eliciting scenarios

> *you are also thinking about your career trajectory/future plans. What do you do?*

While the participants' responses were mixed as to the outcome of the scenario they would choose (i.e., staying vs. leaving the lab), they were clear about their next step. In their decision-making, their pattern of thinking represented the same critical thinking attributes. For example, one participant stated:

> *I would kindly decline the offer to stay in the lab for one extra year. I understand that it would help to develop my professional credentials, but after working so hard in school for so many years, I would like to put all of my skills to use.*

The participant immediately acknowledged the benefits of staying another year in the lab; still, the prospect of advancing their professional trajectory allowed the student to make an informed decision about their future. While the participant's response alludes to them thinking about variables to consider in their choice, their initial decision showed an immediate choice (Deduction). Other participants in the sample echoed similar integration of both Interpretative and Deductive reasoning, "Personally I wouldn't stay another year if I was ready to graduate. While it may add credentials for the professional setting, it also may not make much of a difference." This participant's statement shows their clear decision in one direction based on this scenario. Whereas an inductive statement would entertain thinking around multiple avenues and options to consider for this decision, deductive reasoning shows a defined choice. Further, the participant's inclusion of "may add to credentials for the professional setting" shows that they considered the contextual factors and have a vision of what is at stake, given their prior experiences and knowledge of the scenario and choice. Similarly, another participant shared:

> *I would do my best to help them find a replacement before I leave, so that they're not left empty-handed, but I can get out into the workforce as soon as I can, as that is a large priority of mine.*

While the previous participants made choices to leave the lab, another participant showed similar critical thinking skills, while coming to a different conclusion, "I would stay in my advisor's lab another year. Though it would be tempting to jumpstart my career, a lab related research opportunity is something I would take advantage of while still in college."

The concurrency of Deduction and Interpretation attributes is a unique co-occurrence of critical thinking because they reveal situations where a participant can make a clear choice or decision based on their reasoning, attitudes, and beliefs (Baxter Magolda & King, 2012). In a complex world where individuals bring diverse backgrounds and experiences, identifying patterns where critical thinking skills are similar in reasoning, but different in outcome reveals how CT has been difficult to measure because of its multidimensional and nuanced facets (e.g., Facione, 1990a; Miele & Wigfield, 2014). Whereas some may argue that inductive reasoning (weighing many potential outcomes) is advantageous for students and professionals, recognizing the power of strong deductive reasoning in making clear decisions about their future is especially powerful for undergraduate student participants in this study. For future professionals and leaders, having the ability to leverage experiences amid tough decisions to draw supported conclusions is critical.

As we considered our previous quantitative findings, Interpretation and Deduction were not significantly different in their prevalence to other attributes or between others. Unlike Analysis and Induction, Interpretation, and Deduction did have a weak-moderate, positive relationship, $r(12)= 0.22$, $p> .05$, however, these findings were also not significant with $p<.05$ (Figure 3). These two attributes also were not connected within the same correlation cluster. Once again, initially, the quantitative findings related to these two attributes provided minimal evidence of data that seemed actionable by the project team. The addition of qualitative data analysis provided insights into the Interpretation and Deduction attributes in real-life scenarios and how those in combination appeared in participants' approach to problem-solving.

Less Prevalent or Absent Critical Thinking Attributes

Explanation and Evaluation were two of the three most infrequent critical thinking attributes identified within response data and there were no coded instances of Numeracy (Figure 4). Prompted by diverse scenarios, Explanation and Evaluation had no concurrent occurrences in the data. Both Explanation and Evaluation are critical thinking attributes that strongly depend on interactions with others to justify thinking in verbal or written form or to interrogate the thinking/reasoning of others. This suggests that the lack of occurrences does not reveal that these participants do not have these critical thinking skills, especially since the CCTST assessment demonstrated the presence of these critical thinking attributes (Figure 1C). The question remains then whether these critical thinking attributes are difficult to measure or areas where specific development is needed to strengthen individuals' overall critical thinking skills. These critical thinking attributes should be obtained through personal or professional experiences outside of STEM undergraduate coursework (Butler et al. 2012), and therefore are prime opportunities to further investigation. While these critical thinking attributes might also be developed within coursework as well, is it relevant to consider and investigate how program design ensures opportunities to develop these particular attributes, namely Explanation and Evaluation.

Unlike the previous findings, the lack of qualitative evidence in these attribute areas prompted us to consider if the prompts were too restrictive to elucidate evidence, if it was the approach in general, or if these were truly areas where our students required further opportunity and access. While we do not yet know the exact answer to this wondering, the interpretation of the quantitative analysis in conjunction with the qualitative data analysis is interesting. Explanation, Evaluation, and Numeracy are all found within the same correlation cluster which differs from the other attribute pairings that we found in the more saturated attribute areas. Also, and most apparent, there was a strong, positive correlation between Explanation and Numeracy ($r(12)= 0.69$, $p<.01$), Explanation and Evaluation ($r(12)=0.87$, $p<.01$), and Evaluation and Numeracy ($r(12)=0.54$, $p<.05$) (Figure 3). With there being no significant difference between the quantitative raw scores between each of the attributes, to see these strong relationships between these pairs of attributes stood out. When interpreting these findings with the qualitative absence of these attributes, we found ourselves wondering how and why this might be happening. We share our study's limitations and further discussion, along with implications, in the next sections.

Limitations

We limited the study to a small case of preliminary data within this program. Future investigations aim to include more participants while collecting data at multiple stages of the program. Since the study only involved four critical thinking scenarios, the researchers suggest conducting studies with larger question sets for analyzing critical thinking. The critical thinking skills identified in this study were based on participants' initial written response to the prompts provided. While the scenarios were carefully constructed, researchers acknowledge that they may have inherently limited responses in some of the eight critical thinking attributes. Future studies should re-examine the provided real-world prompts to critically evaluate if there is an opportunity to elicit all eight critical thinking attributes. Additionally, the use of a focus group with semi-structured protocols might be useful to extract additional responses using follow-up prompts. Future studies may continue to combine and elaborate on quantitative and qualitative data collection and analysis to further explore the implications of pre-professional training programs for the development of undergraduate students in STEM and/or other fields.

Discussion & Implications

Preparing the next generation of STEM professionals is vital to our society's progress in this technological world. Understanding the intricacies of how undergraduate STEM students gain complex knowledge, skills, and dispositions is critical as institutions and programs work to advance and attend to workforce demands (Kegan & Lahey, 2009; Pascarella et al., 2011). Still, professional development programs that help students develop critical thinking skills require institutional support.

Undergraduate STEM programs, like the S-STEM program, must assess students' progression. These assessments should include knowledge and quantitative measures and changes in skills and dispositions (e.g., affective) for learning and interacting (Baxter Magolda & King, 2012). Gathering iterative, just-in-time data at various stages, and in various formats can inform program improvement to improve student outcomes. Using data snapshots via the CCTST assessment and qualitative data collection and analysis can help us understand student thinking and experiences to inform our expectations of the impacts of future critical thinking attribute development programs. Still, a just-in-time approach can be expensive and time consuming. We suggest that professional development programs consider the resources and expertise needed to execute a just-in-time approach. Additionally, participants need to be willing to provide feedback and participate in data collection activities.

Seeing the breakdown of critical thinking attributes in the CCTST assessment prompted us to seek further understanding about how these attributes manifested in students' daily thinking to better design programs that could positively impact their overall critical thinking. At first glance, the eight critical thinking attributes appeared to be very similar as they are often used in place of "critical thinking" as a term. As we analyzed early baseline quantitative data, we recognized that while there was no statistical difference in the eight attributes' raw scores, some relationships existed between attributes. Using qualitative analysis and the creation of a detailed critical thinking attribute codebook, we explored the nuances of each critical thinking attribute. We found that many of the attributes occurred simultaneously as students described their decision-making in solving complex problems. As student participants addressed these real-world scenarios, many leveraged their experiences working with K-8 students and on research projects through CURES to consider complex situations with flexibility (Quitadamo et al., 2008; Nelson et al., 2018). For example, one participant shared their thinking process when faced with a challenge, "I normally talk it over with my co-mentor and we figure out from there what's the best option. If we know a lot about what the lesson plan is, we auto correct the mistake or misconception". These circumstances mapped most frequently to the concurrent occasions of Analysis and Induction critical thinking attributes. While sometimes participants approached similar scenarios differently and came to different conclusions, students also showed clarity in their decision-making capacity related to future goals especially with the help of near-peers when possible. These were not aspects of students' critical thinking that were evident in our early understanding of critical thinking using our quantitative findings. The qualitative findings showed us the limited depth of understanding of the nuances of the critical thinking attributes when only looking at the quantitative results

To add to the complexity, the S-STEM program to date has been situated almost entirely within the context of the COVID-19 pandemic, with much of the initial programming and mentoring being interrupted or vastly modified to meet the constraints of the environment. The undergraduate student scholars in this program have experienced a substantial interruption in their learning in terms of access to interactions and collaborative problem-solving in schools (as youth mentors) and lab spaces. The contextual factors of the environment at the time of data collection are important to note, especially when attributes like Explanation and Evaluation require interpersonal interactions within their definition. With a variety of work being done to understand the impact of the global pandemic on individuals and their educational outcomes, this is an opportunity for future research to better understand the potential relationship between contextual factors and critical thinking attainment. In the future, we hope to better understand the intricate development of undergraduate STEM students (including their critical thinking) and programs with and without access to collaborative cohort groups (e.g., communities of practice). This future research direction can inform critical thinking development at the individual level of STEM programs and beyond, and group-level development with or without access to opportunities to collaborate and evolve as a community of learners.

To study a complex, multidimensional construct like critical thinking among undergraduate students and others, researchers must first have a deep understanding of the nuances of such a construct. For this project, which encompasses layers of mentorship, outreach, and research experiences within coursework and beyond, a passive approach and promotion of critical thinking skill attainment may not be enough to create meaningful change or development. As we found, the same is true for measuring critical thinking. Without access to both quantitative and qualitative findings about our students' critical thinking skills, we may have been left with an incomplete picture of how these attributes are related. The attributes manifest in students' daily thinking even when they appear to be missing on the surface. Previous research in this area has called for intentional demonstration and explanation of critical thinking and how students identify critical thinking in their own lives (Mulnix, 2012; Swanwick et al., 2014). Without this deep, mixed-methods approach to critical thinking, we as researchers may have easily missed the nuances of this complex construct in our students. Now equipped with this understanding, we can embed critical thinking attributes within our program interventions and specific disciplines in STEM (Forbes, 2018). For example, programs like ours can elevate the importance of building learning communities and fostering collaboration in STEM spaces for the benefit of active learning and may increase opportunities to achieve the critical thinking attributes of Explanation and Evaluation.

The integration of both quantitative and qualitative approaches enabled us to capture the complex nature of critical thinking. The quantitative data provided us with a baseline to understand the eight critical thinking skills included in our study. However, our qualitative data collection and analysis was paramount for understanding the application of critical thinking skills to real-world problems. For example, our results showed that the critical thinking skills of Evaluation and Explanation had strong correlations in our quantitative data; still, they were less prevalent in the qualitative data. This finding contributes to our comprehension of critical thinking literature by underscoring that recognizing critical thinking skills in an assessment does not automatically result in their successful application in real-world situations. In addition, our results showed that understanding the intricacies of critical thinking skills may enable researchers and practitioners to embed these attributes to the STEM undergraduate programs and beyond; therefore, demonstrating the importance of integrating discipline-based information into the cultivation of critical thinking.

Employers expect undergraduate students to apply critical thinking skills (e.g., Stelter et al., 2020; Xu, 2016; Xue & Larson, 2015). For STEM fields, these skills go beyond discipline-based technical skills and impact everyday interactions and decision-making. Broadening the understanding of the complex construct of critical thinking is an important avenue for future research and practice as we aim to recruit, engage, and develop the future workforce, especially in high-demand STEM fields.

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The authors report there are no competing interests to declare.

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