Supporting Middle School Students' Learning Outcomes and Engagement with NGSS-Aligned Quantum-Infused Science Curriculum

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Supporting Middle School Students' Learning Outcomes and Engagement with NGSS-Aligned Quantum-Infused Science Curriculum (Evaluation)

Abstract

This study informs the engineering education community about the what, how, and why of introducing quantum technologies into K-12 learning spaces. While incorporating quantum concepts in K-12 is relatively new, it presents a wide range of learning opportunities across different subject areas. Nevertheless, challenges persist in teaching basic quantum information science and engineering (QISE) concepts, especially at the middle school level. Relatedly, teachers have expressed concerns regarding the lack of training, educational materials, and available time within their school schedules. Despite these hurdles, research points to the importance of reaching middle school students to establish fundamental QISE skills and cultivate engagement and interest in QISE-focused degrees and careers.

Teaching students about emerging quantum technologies may offer potential solutions to address these challenges. Quantum technology, which applies the principles of quantum mechanics to create innovative solutions, has driven advancements in computing, secure communication, and materials science by harnessing the distinctive properties of quantum states. In this study, we developed a middle school science curriculum that was infused with QISE concepts and aligned with Next Generation Science Standards. We assessed its impact on the science learning outcomes and multidimensional engagement of 873 students. Our curriculum, designed to incorporate the essential science and engineering practices of "Analyzing and Interpreting Data" and "Constructing Explanations and Designing Solutions," guided students from the foundational concepts of Newtonian physics to the more advanced context of Einsteinian physics. This learning progression encompassed disciplinary core ideas ranging from the "History of Earth" to "Waves and Electromagnetic Radiation," as addressed in the middle school science NGSS documents [16]. Our study results show statistically significant improvements in students' learning of fundamental quantum concepts, as well as some observable changes in their multidimensional engagement. Our discussion highlights the promise of embedding quantum concepts into the existing three-dimensional learning of middle school science education, as prior quantum-based learning materials either do not highlight NGSS in their curricula or their primary focus is on high school and post-secondary education levels. We also explore potential reasons for the consistency in students' multidimensional engagement and provide insights for researchers and educators interested in incorporating the teaching of emerging quantum technologies and their societal applications.

KEYWORDS

Quantum education, K-12 STEM education, pre-college science and engineering education.

Motivation and Background

QISE is becoming increasingly important in various sectors of society. They are seen as transformative forces that affect scientific research, the development of hardware and software in engineering, experimentation practices, and commercialization of products and services [1]. Quantum computers are one of the technological and engineering-based applications of QISE, which is still in its infancy, but research indicates that the recognition of the importance and impact of quantum computers and computing is worldwide [2], [3]. The demand for people who are trained in QISE has gone up a lot because there are now many different jobs in different fields that need this knowledge. So, there's a big push around the world to make sure people get the right education and training for these jobs [1]. Therefore, scholars in this field suggest that one of the audiences that needs to be educated about quantum computing and its applications are pre-college students [4], [5]. More specifically, they advocate the need of teaching contemporary physics earlier in the curriculum because introducing modern and quantum physics before college are interesting and can potentially motive students to learn physics in the future years [4], [5].

Drawing from prior recommendation [4], researchers advocated for teaching counterintuitive quantum concepts based on conceptual ideas rather than intricate mathematical formulations to pre-college students [6]. Although teaching quantum mechanics to students without relying on complex mathematical formalism poses a significant challenge, it does not imply an inherent complexity that renders quantum physics impossible to teach [7]. Instead, existing quantum education efforts point to difficulties that demand attention, urging students to embrace a new, non-deterministic way of thinking and develop a profound understanding of scientific models and their limitations [8]. Therefore, there is an emphasis in the literature regarding the ability to do fluidly transition between different models and representations of learning quantum-based concepts as well as on the necessity of accurate prior knowledge construction to comprehend quantum physics [4]. However, existing studies that attempted to teach quantum concepts at the pre-college level were very limited [9], [10], [11], [12]. Therefore, this study took the initiative to present how an effective quantum-infused science curriculum can be developed for middle school students and present results regarding the change in middle school students' science learning outcomes and multidimensional engagement.

Context for the Study: IQ-PARC Project

This paper is a component of a broader initiative called Innovation in Quantum Pedagogy, Application, and its Relation to Culture (IQ-PARC), which is funded by the Department of Defense (DoD). IQ-PARC aims to foster a cultural shift towards quantum technologies by bridging the gap between quantum and non-quantum communities through education, collaboration, and public outreach [13]. The diverse IQ-PARC research team, consisting of engineers and scientists from various backgrounds, focuses on a crucial objective: creating instructional materials with a quantum focus, while incorporating minimal mathematics for middle and high school teachers and their students.

During the initial two years of the project, the team successfully accomplished its mission. Collaborating with middle school science teachers, they designed, implemented, and tested instructional content and materials infused with QISE concepts, specifically highlighting the concepts of randomness and quantum random generators, which are fundamentals to quantum computing applications [14]. The developed materials were piloted during Teachers' Quantum Workshop (TQW) organized by IQ-PARC research team, and the effectiveness of the quantum-infused instructional unit on students' science learning outcomes and multidimensional engagement was evaluated.

This study employs a Design-Based Research (DBR) approach, which forms the fundamental methodology shaping the alignment of the Next Generation Science Standards (NGSS) with quantum-infused instructional content. Although we did not intend to investigate study participants' learning outcomes based on NGSS components, we highlighted how the Framework for K-12 Science Education [15] and NGSS [16] contributed to the product design process of our methodology. Accordingly, the next section explains the details of the NGSS-aligned quantum-infused instructional unit with a brief emphasis on the design aspects.

NGSS-Aligned Quantum-Infused Science Curriculum as a Product Design

NGSS represents standards as practical application of knowledge by formulating them as Performance Expectations (PEs) that incorporate the three dimensions outlined *in the Framework for K-12 Science Education* [15]. This amalgamation of core ideas, practices, and crosscutting concepts is termed as three-dimensional learning [16]. NGSS PEs differ from state standards because it emphasizes the integration of all three dimensions by requiring students to demonstrate their knowledge in science and engineering practices [17]. In accordance with the recommendations of [17] on constructing instruction to foster comprehension of NGSS PEs, this paper shows how our study employed specific guiding design principles and associated elements/practices that played a crucial role in developing an innovative approach to science teaching and learning. Table 1 illustrates the selected design principles and elements/practices that guided this study's quantum-infused science curriculum development process.

Table 1

Design requirements *principles and elements/practices that guided quantum-infused science instruction*

Requirements/ Principles	**Propositions/Elements/Practices**
Up-to-date documentation: Alignment with NGSS	Expectations and instructions were presented explicitly with clear NGSS PEs in the unit.
Interdisciplinary approach	Various scientific disciplines were integrated and collaboration between different domains of knowledge (i.e., computer science, quantum computing, physics) were encouraged.
Opportunities for communication and creativity	Teacher's Quantum Workshop organized in Summer 2022 and 2023 provided a set-up for teachers to listen quantum fundamentals from scientists, convey their questions, and interact with the projects team and other teachers to apply what they learn in their teaching during their formal curriculum plan.
Continuous improvement	Iterative revisions during the first two years of the project helped improve the instructional design, implementation, and evaluation processes.

In this paper we specifically elaborate on the first design principle that aligned the expectations and instructions of the quantum-infused science learning unit with NGSS PEs. With our focus on developing understanding of randomness and probability in middle school level physics, two related NGSS PEs included:

1. MS-ESS1-4 (Middle School, Earth and Space Sciences, DC 1, fourth PE, in NGSS Topic History of Earth), and
2. MS-ESS3-1 (Middle School, Earth and Space Sciences, DC 3, first PE, in NGSS Topic Earth's Systems).

Although the selected PEs initially addressed classical physics-related concepts, the classic concept of randomness was strategically utilized as a bridge to introduce the concept of randomness in quantum computers. In this way, the chosen PEs provided a foundation for students to make a perceptible observation of randomness in the radioactive decay process, facilitating a smoother transition to the abstract conceptualization of quantum randomness in quantum random number generators.

Additionally, K-8 Computer Science state standards were also incorporated into the unit with the following core practices: 6-8. DI.2 (Grades 6-8, K-8 Computer Science, second practice, in Core Concept Data & Information), 6-8. DI.3 (Grades 6-8, K-8 Computer Science, third practice, in Core Concept Data & Information), 6-8. DI.4 (Grades 6-8, K-8 Computer Science, fourth practice, in Core Concept Data & Information), 6-8.CD.4 (Grades 6-8, K-8 Computer Science, fourth practice, in Core Concept Computing Devices & Systems). These core practices played a pivotal role in guiding the instructional approach of our product design development. These standards directed end users of this product design (teachers) to facilitate active experimentation by students, specifically involving the utilization of random binary numbers. To bring this concept to life, we organized a dynamic learning experience by live streaming and generating random binary numbers through a real online quantum lab – called ANU Quantum Optics group – situated in Australia. This narrative or the careful construction of storyline [17] was designed to guide students in constructing a scientific explanation that elucidated why the concept of randomness in the classical world (nature) is predictable and fundamentally distinct from the randomness experimented in the quantum world, particularly within the context of quantum computers. The purpose of this step was to foster a comprehensive understanding of why randomness behaves predictably in the classical physics while exhibiting unique characteristics in the quantum domain [14].

Methods

This study integrated two methods, conjecture mapping as a method of DBR and a pretest posttest research design to examine the desired outcomes of IQ-PARC project. Conjecture mapping involves the explicit delineation of specific conjectures and their anticipated interactions to facilitate learning [18]. Like how the flight of an airplane is contingent on achieving adequate lift, designs alone cannot directly yield outcomes; rather, they necessitate *mediating processes*. Consequently, each curriculum design must embody certain aspects that undergo mediating processes, articulated as *design conjectures* [18]. These mediating processes eventually culminate in outcomes guided by *theoretical conjectures*. Figure 1 summarized the hypothesized conjecture mapping in the context of this study.

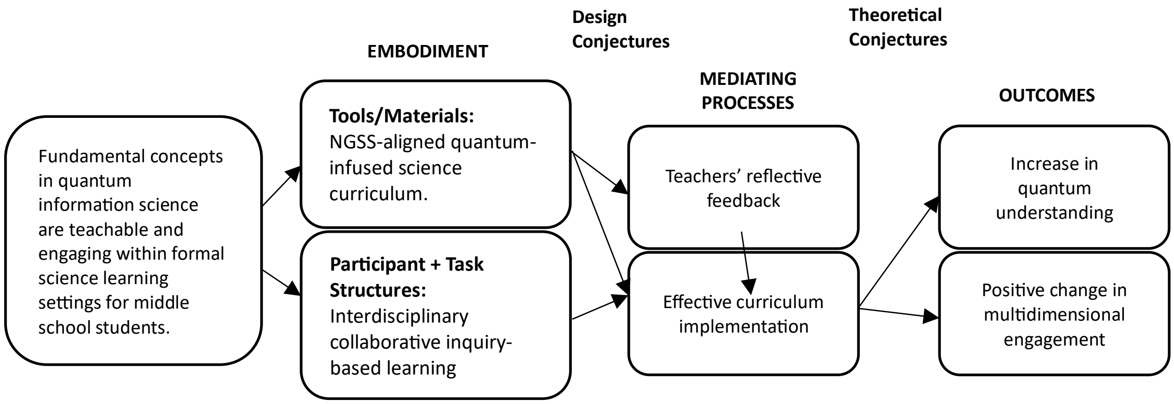

Figure 1: *Hypothesized conjecture mapping of this DBR study*

As Figure.1 illustrates high level conjecture, that is derived from the problem analysis based on prior work posits that fundamental concepts in quantum information science are teachable and engaging within formal science learning settings for middle school students. The *embodiment*, followed by high level conjecture, refers to how the researcher, acting as *the designer*, operationalizes the high-level conjecture into NGSS-aligned quantum-focused teaching and learning experience for middle school teachers and their students. Then, the design is followed by the anticipated observable interactions by participant teachers who joined professional development program to provide their feedback and enacted on the curriculum design through teaching experiment/implementation. Lastly, the learning and motivation-based outcomes of this study's conjecture mapping encompassed participant students' science learning outcomes and multidimensional engagement.

In addition to the conjecture mapping methods for the curriculum design development process, this exploratory empirical study embodied pretest posttest design to evaluate the premises of project implementation as desired outcomes. Accordingly, we specifically presented the quantitative results/desired outcomes coming from the pretest and posttest research approach.

Pretest Posttest Research Design

We utilized pre- and post-research design with no control group to examine the effectiveness of our instruction on enhancing middle school students' learning and engagement of randomness as a concept in quantum computing [14]. The last of our design procedure involved administering a learning assessment test and a multidimensional engagement survey to evaluate students' understanding of randomness and assess their level of multidimensional engagement focusing on behavioral, emotional, cognitive, and social components.

Participants

The main participants for this research study were 873 middle school students enrolled in public schools in the Midwest region of the United States. A total of seven public schools from four different school corporations participated in our study. Sociodemographic data of the schools was received from the publicly available 2023 State Department of Education website. Table 2 shows the overall sociodemographic characteristics of the participating schools.

We collected student data by working with 10 middle school science teachers in this study. All teachers participated in the professional development workshop designed and delivered by the project team and then implemented the unit after the professional development workshop at different dates/times according to their yearly teaching schedule. The average number of years of science teaching experience among all the teachers was 15 years. Four teachers were female, and six teachers were male.

The study was reviewed and approved by the University IRB office. We collected informed consent from parents and students using consent and assent forms, and our data handling procedures were such that all participants' information remained confidential and anonymous throughout the data collection and analysis process.

Table 2

Sociodemographic of the schools (2024)

Characteristics	High Ground (C1*)		East Side (C1)		Deep Valley (C2*)		Jr. Jefferson (C4*)		Newton (C3*)		Right Valley (C1)		Down Village (C1)	
	n	%	*n*	%	*n*	%	*n*	%	*n*	%	*n*	%	*n*	%
Gender														
Female	356	49	265	50	367	49	497	49	99	52	149	48	346	49
Male	366	51	263	50	379	51	524	51	90	48	162	52	353	51
Grade Level														
6th	248	34	191	36	244	33	0	0	54	29	110	35	223	32
7th	230	32	162	31	260	35	507	50	75	40	107	34	218	31
8th	244	34	175	33	242	32	514	50	60	32	94	30	258	37
Race/Ethnicity														
White	548	74	413	77	611	82	402	39	163	80	239	77	396	56
Hispanic	85	12	58	11	98	13	338	32	38	19	56	18	186	26
Multiracial	35	5	19	4	13	2	76	7	2	1	7	2	37	5
Black	42	6	42	8	3	0	219	21	1	0	9	3	89	13
Asian	25	3	7	1	9	1	4	0	0	0	0	0	2	0
American Indian	4	1	0	0	5	1	1	0	0	0	0	0	0	0
Native Hawaiian	0	0	0	0	2	0	3	0	0	0	0	0	0	0
Meal Status														
Free/Reduce	260	35	122	24	327	44	777	74	141	69	129	41	383	54
Paid	479	65	387	76	414	56	266	26	63	31	182	59	327	46

*C1, C2, C3, and C4 represent four different school corporations.

As Table 2 illustrates that the female or male ratio of students were similar across different schools. The distribution of grade levels in the majority of the schools was also similar. Only Jr. Jefferson lacked 6th-grade students, as it is classified as a Senior Junior High School. The race/ethnicity data indicates that most schools have predominantly White student populations. The meal status data reveals that three out of seven schools had a higher percentage of students registered for the National School Lunch Program (NSLP), suggesting these schools have a relatively high percentage of students with low socioeconomic status, who are eligible to receive low-cost or free lunches [20].

Data Sources and Analysis

Post-Teachers Quantum Workshop (TQW) debrief interviews

In the summer of 2022, all participating teachers consented to partake in post-TQW debrief interviews, which began with a comprehensive introduction covering the interviewers' identities, the purpose of the interview, informed consent details, recording permissions, and preliminary comprehension checks conducted via Qualtrics. The interview structure included eight to ten main questions supplemented by follow-up and probing queries, spanning approximately 60 minutes, and concluded by thanking the participants, inviting further questions, and emphasizing confidentiality. Interviews were recorded using Microsoft Teams for both audio and visual documentation. The formulation of interview questions was grounded in prior research [21], [22] [23], focusing on exploring teachers' motivations for teaching quantum information science, their ability to integrate quantum concepts into existing curricula, and the perceived relevance and impact of such content on standards-based science education. Transcriptions of these interviews were performed using Microsoft Teams, with subsequent coding and thematic analysis conducted within Microsoft Excel. This analysis was steered by motivation theories, particularly the Expectancy-Value Theory [25], which helped in pinpointing significant themes and coding the responses accordingly.

Science learning assessment test

Our design encompassed the use of pre- and post-assessment tests. These assessments addressed research inquiries regarding students' science learning outcomes. Specifically, the science learning assessment aimed to measure the comprehension of fundamental quantum concepts among middle school students after their participation in a week-long quantum-infused science curriculum unit implementation. The creation of these assessment items involved a thorough review of existing literature and textual materials on quantum physics education, along with consultations with field experts. The content of the assessment questions adhered to different DCIs ranging from the “History of Earth” to “Waves and Electromagnetic Radiation,” as addressed in the middle school science NGSS documents [18]. All questions in the assessment test underwent scrutiny for readability and compatibility through pilot testing with a small group of students ($n = 3$) and we incorporated feedback and revisions from teachers during the TQW. The assessment tool comprised 13 items, including five multiple-choice questions assessing knowledge of classical and quantum physics concepts (e.g., half-life of Carbon-14 atoms) and eight open-ended questions requiring the application of understanding to real-world scenarios (e.g., popcorn analogy, randomness in a real quantum random number generator).

Multidimensional student engagement survey

This survey measured different components of student engagement including behavioral, emotional, cognitive, and social aspects, in the context of science learning. The validated survey was called “The Math and Science Engagement Scales” [26], [27] and consisted of 25 questions, with seven questions related to behavioral engagement (labeled Behavior1 to Behavior7), six questions related to emotional engagement (labeled Emotion1 to Emotion6), six questions related to social engagement (labeled Social1 to Social6), and six questions related to cognitive engagement (labeled Cognitive1 to Cognitive6). The students rated their engagement using a 5-point Likert scale ranging from "Not at all like me" to "Very much like me."

We administered both the science learning assessment test and the multidimensional student engagement survey at two-time points. Participant teachers of this study were asked to administer the pre-assessment and pre-engagement survey before the unit implementation began, and they administered the post-assessment and post-engagement survey immediately after the unit implementation ended. Pre- and post-mean scores were calculated for both measures, and paired-samples t-tests were conducted to determine if the differences were statistically significant. The analyses were performed using R Studio and IBM SPSS Statistics 28.0. Statistical assumptions were assessed for data normality through skewness and kurtosis values, as well as Q-Q plots. Skewness values for all variables indicated moderate to low skewness, falling between -1 and 1. Similarly, kurtosis ranged between -2 to +2, meeting acceptable criteria for ensuring data homogeneity. The assumption of normality for subsequent statistical analyses was reasonably satisfied. The Shapiro-Wilk normality test for pre-scores yielded a test statistic of .976, suggesting that the distribution of pre-scores was approximately normal ($p > .05$). Similarly, for post-scores, the Shapiro-Wilk test produced a statistic of .957, indicating that the distribution of post-scores was also approximately normal ($p > .05$). Therefore, we were able to conduct paired-samples t-tests for the comparison analyses.

Given that the science learning assessment test included both open-ended and multiple-choice questions, we utilized an assessment rubric based on the categories of claim, evidence, and reasoning [28]. Multiple-choice questions were scored on a true-false basis, while open-ended responses were assessed according to three categories: zero for those not meeting any of the three criteria, one for demonstrating conceptual understanding in one category, and two for displaying full conceptual understanding with claim, evidence, and reasoning. Due to the uniqueness of responses, manual grading was necessary. To enhance reliability, three raters from the fields of education and engineering were involved in the grading process. Inter-rater reliability was ensured through Krippendorff's alpha coefficient, with a custom Python implementation yielding a mean alpha value of .84, indicating good agreement among the raters [29].

To ensure the trustworthiness of the study, we took several measures. Anecdotal notes were kept for both teacher performance and students' reactions to enhance confirmability. Findings were detailed in writing to demonstrate that the study's results could be applicable to other situations, ensuring transferability.

Results

The conclusions of this study were presented as *design* and *theoretical conjectures*. Design conjectures included findings from teachers' reflective feedback after the TQW. Teachers were asked about their motivation and perspectives of teaching quantum-infused science content in addition to their feedback on the curriculum design (*embodiment*). Theoretical conjectures, on the other hand, was looking for bridging the gap between *mediating processes* and *desired outcomes.* The quantitative results that show the change in students' pre-to-post scores of learning outcomes and multidimensional engagement was used to interpret how the mediating processes of teacher involvement in the curriculum design process along with their feedback and curriculum implementation had an impact on the desired outcomes.

Teachers' motivation and perspectives on teaching quantum-infused science content

During the interviews, middle school teachers answered eight to ten questions focused on their motivations for joining TQW, their understanding of quantum concepts as educators, and their expectations for how teaching quantum science would enhance students' skills in science and engineering. We analyzed the responses using initial or open coding, identifying distinct patterns in the teachers' answers. These patterns were further examined through axial coding, which linked the themes across different questions, enhancing the understanding of the teachers' perspectives. The validity of these identified themes—such as *Pragmatic Considerations*, *Professional Development and Growth*, *Understanding the Value of Quantum Science*, and *Student Engagement and Curiosity* — was confirmed by another expert in qualitative social sciences research, ensuring the robustness of the findings.

Pragmatic Considerations

Teacher expressed a proactive desire to understand quantum concepts before they become integrated into educational standards, viewing this knowledge as a professional advantage. Several teachers, like Teacher Mateo, appreciated the dual benefit of acquiring innovative ideas for science teaching while also obtaining funding for classroom resources.

> *"…So, that's something that we enjoy doing, we enjoy learning new things in the classroom, trying to figure out how to implement that into our classrooms. And you know, I will be honest about it. Some of it is financial as well. We like to go to workshops that pay you. I am going to be truthful and honest about it."*

Professional Development and Growth

Teachers emphasized their motivation to enhance their understanding of complex topics, engage in meaningful professional development, and acquire new teaching methods and resources. Teachers like Kiara were motivated by the desire to improve their ability to teach challenging concepts such as radiometric dating; she stated,

> *"I think my main motivation was when it [the workshop flyer] was talking about the radiometric dating, because I've always had a difficult time... So, that was a big motivation for me is to learn more about that. And to be able to teach that radiometric dating, part of it in a way that they [students] could understand."*

This sentiment was echoed by another teacher, who valued the continuous professional development and the acquisition of innovative teaching approaches facilitated through collaborations. Collectively, these motivations showcase teachers' proactive approach to professional development, highlighting their dedication to enhancing both their teaching skills and their students' learning experiences.

Understanding the Value of QISE

Teachers openly admitted that the quantum-infused unit introduced concepts that were initially unfamiliar to them, but ultimately enhanced their fundamental understanding of quantum science and its real-world applications. This newfound knowledge was something they were keen to transfer to their students, emphasizing the practical value of quantum technologies in everyday life. For instance, Teacher Marisa articulated her hopes for student outcomes, stating, *"But I would at least hope they would recognize that it has value for keeping their personal information secure so that someone can't steal your credit card numbers...they at least walk with the appreciation of the people who are doing this, are doing something that matters."*

Similarly, Teacher Eleanor highlighted the engaging nature of real-life applications in learning, observing,

"So, I think that they will be interested in the fact that it [quantum] has a real-life application. Yeah, they like it because they're making. They're like they're doing real science."

These statements reflect this theme, illustrating how teachers recognized the importance of integrating quantum education into the curriculum not just to enhance student understanding but also to increase their interest in contemporary scientific applications. This aligns with the Expectancy-Value Theory [25] which posits that the value students perceive in a learning task and their expectations of success significantly influence their motivation and engagement. By presenting quantum science not only as a valuable academic subject but also through its practical applications, teachers statement shows that QISE teaching at the middle school level can effectively raise students' perceived utility value of the content.

Student Engagement and Curiosity

This theme highlights the participant teachers' nuanced expectations for their students' reactions to quantum-infused content, emphasizing the potential for increased confidence and cognitive engagement. Teachers like Jessica anticipate a rise in student curiosity and engagement, illustrated by her experience with an honors student who showed great enthusiasm and attentiveness:

"When I asked students 'Are you familiar with quantum?', at least one student said 'Woo'. She was very excited."

This example reflects the expectation that engaging content can stimulate interest among students who are already inclined towards science. Conversely, Teacher Wayne notes the importance of making quantum learning hands-on and accessible, recognizing that even simplistic interactions, like using a quantum number generator, can foster a foundational exposure to quantum concepts. His approach underlines the belief that:

"...at any level, whether it's kindergarten through ninth grade, getting them exposed to that... they have a better understanding of, maybe a path they want to take."

Collectively, these insights reveal that while quantum content is challenging, it can significantly engage students if delivered in a fun and comprehensible manner, aligning well with their existing interests and enhancing their educational journey in science.

Conceptual Understanding and Focus

This theme focusing on teachers' conceptual understanding of quantum from TQW revealed how they personally interpret quantum concepts influenced by their experiences and prior knowledge. This theme is distinct from the previous four, which centered on teachers' motivations; here, the focus shifts to their perspectives on teaching the quantum-infused curriculum. Teachers defined quantum in terms of "A Concept Associated with Randomness" and "Things in Small Scale". For example, Teacher Marisa related quantum to microscopic particles, stating:

> *"...I look at quantum as being theories and rules and things that we're studying about. The really, really small particles that are really even smaller than electron, proton, neutron or explain the way we see them behave in unexpected ways."*

Similarly, Teacher Thomas described quantum as embodying true randomness, illustrating his struggle to convey this concept to students:

> *"I guess it [quantum] will be like true randomness... Quantum randomness like the websites that you give us the actual quantum computer versus just a random number generator."*

These descriptions highlight the challenges teachers face in translating complex quantum theories into understandable content for students, reflecting their efforts to prevent misconceptions and foster accurate scientific understanding.

Pedagogical Thoughts and Concerns

This last theme focused on teachers' perspectives concerning the pedagogical aspects of the quantum-infused science learning content, distinct from previous themes. Teachers shared insights into both the strengths and weaknesses of the curriculum design, along with their concerns about how well it integrates into existing educational frameworks. For instance, Teacher Eleanor pointed out the relevance of the content to students' lives but critiqued its connection to the broader curriculum:

> *"The weaknesses would be that it doesn't make true connections to the curriculum, so it's kind of forced. The strengths would be that it shows the kids applicable science like this is something that is applicable to your life."*

Additionally, Teacher Wayne expressed concerns about ensuring the curriculum aligns with shifting educational standards, emphasizing the need for grade-specific tailoring:

> *"You know with the shifting standards in seventh grade, you know making sure that it shifts towards the seventh grade meets the standards."*

These comments reflect a broader theme of "Curricular Integration Concerns," where teachers acknowledged the challenges of teaching advanced concepts like quantum science in middle school settings. They expressed apprehensions about their own comfort with the content and its comprehensibility to students, as Teacher Marisa highlighted the intimidation of teaching complex topics without full mastery:

"...If I have a choice, quantum being already such a very hard concept, even for adults to wrap their minds around, it's very intimidating to teach that to students when you know that you don't really understand it completely."

Despite these challenges, teachers' thoughts and concerns underscored a commitment to enhancing student engagement with scientifically relevant topics, balanced by the practical need to fit these innovations within the constraints of curriculum standards and teacher preparedness.

To summarize, the exploration of participant teachers' motivations, expectations, and concerns through post-TQW debrief interviews revealed a multifaceted perspective on the integration of quantum science into the curriculum. Teachers were motivated by the potential for professional growth and practical benefits and recognized the value of quantum concepts in engaging and enriching student learning. However, they expressed significant challenges related to curricular alignment, the complexity of quantum concepts, and the necessity for teacher preparedness.

Science learning outcomes and multidimensional engagement scores

We investigated the change in students' science learning outcomes and multidimensional engagement from the start to the end of the implementation. Paired samples t-tests were used for each measure. Descriptive statistics, including mean and standard deviation values for each measure, are given in the tables presenting statistical test results.

For science learning outcomes, the paired samples t-tests results indicated a statistically significant increase in post-assessment scores compared to pre-assessment scores ([$t(872) = 18.72$], $p < .001$), with a moderate to large practical significance ($d = 0.63$) [23]. For the multidimensional engagement components, statistically significant changes were found between pre- and post-surveys for emotional ([$t(778) = 6.28$], $p < .001$), cognitive ([$t(773) = 4.09$], $p < .001$), and social ([$t(770) = 5.78$], $p < .001$) engagement, while no statistically significant difference was found for the behavioral engagement scores ($p > .05$). Table 3 displays the paired t-test results for science learning outcomes and multidimensional scores along with the corresponding effect size values.

Table 3

Paired, two-tailed t-test results for science learning outcomes and engagement scores

Science Learning Outcomes													
Scale	**df**	**Pre-test**				**Post-test**				**Diff.**	***t***	***p***	***Cohen's d***
		Mean	S.D.	S.E.	Max	Mean	S.D.	S.E.	Max				
Science Assessment Test	872	28.87	9.69	.33	56.00	34.08	10.37	.35	56.00	5.21	18.72	<.001	.63

Multidimensional Engagement													
Subscale	**df**	**Pre-survey**				**Post-survey**				**Diff.**	***t***	***p***	***Cohen's d***
		Mean	S.D.	S.E.	Max	Mean	S.D.	S.E.	Max				
Behavioral	778	2.96	.34	.01	3.86	2.98	.37	.01	5.00	.019	1.50	.132	-
Emotional	778	2.67	.52	.02	4.00	2.78	.48	.02	4.20	.107	6.28	<.001	.48
Social	773	2.91	.49	.02	4.20	2.99	.48	.02	5.00	.078	5.78	<.001	.53
Cognitive	770	2.79	.47	.02	4.17	2.90	.45	.02	5.00	.105	4.09	<.001	.50

The practical significance values revealed that the pre- and post-scores for emotional (d = .48), social (d = .53), and cognitive (d = .50) engagement demonstrated a moderate effect size, suggesting a noteworthy change in how middle school students engaged emotionally, socially, and cognitively during their learning of the quantum-infused science unit.

Discussion

This study forms a segment of a larger DBR project that blends conjecture mapping in educational research with a pretest-posttest design to quantitatively measure effects. It specifically scrutinizes the elements of a quantum-infused curriculum unit that is aligned with NGSS, focusing on how design and theoretical conjectures influence students' science learning outcomes and their engagement on multiple dimensions.

The study uncovers that the design conjectures involve both the curriculum and the educators implementing it. Insights from post-TQW debrief interviews reveal that teachers play a crucial role in the curriculum's success through their motivated implementation and feedback. This approach, combined with ongoing professional development and resource support for teachers, aims to bridge the gap between the ambitious potential of quantum science education and the practical challenges of teaching it effectively.

Theoretically, this study highlights the importance of aligning innovative scientific content with NGSS performance expectations, which has been shown to significantly improve students' science learning outcomes. This alignment is believed to enrich the instructional strategy, which is echoed in previous research that integrated NGSS into middle school curricula with a focus on novel scientific applications [19]. Additionally, the curriculum enhances students' emotional, cognitive, and social engagement, but not necessarily their behavioral engagement. This suggests that while the quantum-infused curriculum increases enjoyment and intellectual participation, further investigation into enhancing behavioral engagement is needed. Therefore, our study is noteworthy for its novelty, as most existing attempts to introduce K-12 quantum-related content have not aligned with NGSS components and have not integrated DBR methods with quantitative measures like other quantum-focused prior studies for middle school students [30], [31]. In contrast to prior research suggesting that students may not perceive learning quantum physics as relevant [32], our findings targeting engagement-focused outcomes portray a different picture, showing meaningful increases in affective and cognitive aspects of student involvement in learning innovative science concepts.

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